COMPARISON OF TRANSPORT FUELS

FINAL REPORT
(EV45A/2/F3C)

to the

AUSTRALIAN GREENHOUSE OFFICE

on the Stage 2 study of

Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

By

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Acronyms

3C	Three-way catalytic converter
ABARE	Australian Bureau of Agricultural and Resource Economics
ACTION	Australian Capital Territory Internal Omnibus Network
ADR	Australian Design Rule
AFCP	Alternative Fuel Conversion Program
AGA	Australian Gas Association
AGO	Australian Greenhouse Office
AIP	Australian Institute of Petroleum
ALPGA	Australian Liquefied Petroleum Gas Association
ANGVC	Australasian Natural Gas Vehicles Council
AQIRP	Air Quality Improvement Research Program
BD	Biodiesel
BD100	100% Biodiesel
BD20	20% Biodiesel
BRS	Bureau of Resource Science
BTCE	Bureau Of Transport and Communications Economics
CAD	California Diesel
CBD	Central Business District
CEE	Canola Ethyl Ester
CFC	Chlorofluorocarbons
CH_4	Methane
CME	Canola Methyl Ester
CMU-ET	Carnegie Mellon University Equivalent Toxicity
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRPT	Continuous Regenerating Particulate Trap
CUEDC	Composite Urban Emissions Drive Cycle
DAFGS	Diesel and Alternative Fuels Grants Scheme
DOC	Dissolved Organic Carbon
DOE	Department of Energy (United States)
E100	Ethanol
E10P	10% Ethanol dissolved in petrol (petrohol)
E15D	15% Ethanol dissolved in diesel fuel
E93	93% Ethanol
E95	95% Ethanol
ELR	European Load Response
EPA	Environmental Protection Agency (US)
	Environment Protection Authority (NSW & VIC)
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ERDC	Energy Research and Development Corporation
ESC	European Stationary Cycle
ETC	European Transient Cycle
ETSU	Energy Technology Support Unit

FAMAE	Fatty Acid Mono Alkyl Ester
FAME	Fatty Acid Methyl Ester
FFC	Full Fuel Cycle
FQR	Fuel Quality Review
FT	Fischer-Tropsch
FTD	Fischer-Tropsch Diesel
GCV	Gross Calorific Value
GJ	Gigajoule; unit of energy; 1 GJ = 1 x 10^9 *J*
GHG	Greenhouse Gases
GMO	Genetically Modified Organisms
GTL	Gas to Liquid
GVM	Gross Vehicle Mass
GWP	Global Warming Potential
HC	Hydrocarbons. In this report, HC is used for non-methanic hydrocarbons.
HD5	Standard for LPG such that it is primarily propane.
HDV	Heavy Duty Vehicle
HGV	Heavy Goods Vehicle
IANGV	International Association for Natural Gas Vehicles
IEA	International Energy Agency
IEA/AFIS	International Energy Agency/Alternative Fuels Information System
LCA	Life Cycle Analysis
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LEV	Low Emission Vehicle
LNG	Liquid Natural Gas
LPG	Liquefied Petroleum Gas
LSD	Low Sulfur Diesel
MJ	Megajoule; unit of energy; 1 MJ = 1 x10^6 *J*
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NG	Natural Gas
NGGIC	National Greenhouse Gas Inventory Committee
NGV	National Gas Vehicle
NMHC	Non-methanic Hydrocarbon
NMVOC	Non-methanic Volatile Organic Compound
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory
NSW	New South Wales
OEM	Original Equipment Manufacturer
OEHHA	Office of Environmental Health Hazard Assessment (of the Californian EPA)
OXC	Oxidation Catalyst
OHS	Occupational Health and Safety
PAH	Polycyclic Aromatic Hydrocarbons

PM	Particulate Matter
PM10	Particulate matter below 10 μm diameter
PULP	Premium Unleaded Petrol
REE	Rapeseed Ethyl Ester
RME	Rapeseed Methyl Ester
RMIT	Royal Melbourne Institute of Technology
RTA	Roads and Traffic Authority (NSW)
SAE	Society of Automotive Engineers
SO_2	Sulfur Dioxide
SO_x	Oxides of Sulfur
SOF	Soluble Organic Fraction
SULEV	Super Ultra-Low Emission Vehicle
THC	Total Hydrocarbons, being the sum of NMHC and methane.
TSP	Total Suspended Particles
TTVS	Trans Tasman Vehicle Standards
ULS	Ultra-Low Sulfur Diesel
US	United States of America
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds
VOME	Vegetable Oil Methyl Ester
WVU	West Virginia University

Glossary of Terms

Acetaldehyde

CH_3CHO emission component of the exhaust gases of combustion engines; an air toxic, presumably carcinogenic.

Additive

additives are added to the fuel in small amounts to improve the properties of the fuel. For instance, anti-sludge additives prevent the deposits of carbon and tar on the inlet valves and other engine parts.

Air/fuel ratio

Mass ratio of air to fuel inducted by an engine. See also stoichiometric ratio.

Alcohol

Group of organic compounds, derived from hydrocarbons, which one or more hydrogen atoms replaced by hydroxyl (OH) groups.

Biodegradability

the capability of a substance to decompose into harmless elements

Biodiesel

automotive fuel consisting of esterified vegetable oils such as rapeseed methyl ester and soybean methyl ester

Catalyst

1. Substance that influences the speed and direction of a chemical reaction without itself undergoing any significant change.

2. Catalytic reactor which reduces the emission of harmful exhaust gases from combustion engines.

Canola Oil

A vegetable oil made from canola. It is similar to rapeseed oil but with less crucic acid and glucosinolates.

Cetane number

A measure of the ignition quality of diesel fuel based on ignition delay in an engine. The higher the cetane number the shorter the ignition delay and the better the ignition quality. The cetane number is based on the ignition quality of cetane ($C_{16}H_{34}$) and heptamethylnonane.

Compression ratio

The ratio of the volume of the combustion chamber at the beginning of the compression stroke and the volume of the chamber at the end of the compression stroke.

Compression ignition engine

Internal combustion engine with an ignition caused by the heating of the fuel-air mixture in the cylinder by means of compression. This compression causes a rise in temperature and pressure which make possible the spontaneous reaction between fuel and oxygen. Also called a diesel engine.

Crude; crude oil

crude mineral oil. Naturally occurring hydrocarbon fluid containing small amounts of nitrogen, sulphur, oxygen and other materials. Crude oils from different areas can vary enormously.

DI-engine

direct injected engine; combustion engine with a direct injection of fuel into the combustion chamber.

Diesel engine

1. Combustion engine running on diesel oil;

2. other name for a combustion engine with compression ignition (named after Rudolf Christian Carl Diesel (1858-1913), one of the founders of the combustion engine principle).

Diesel (oil)

1. A mixture of different hydrocarbons with a boiling range between 250º and 350ºC;
2. A fuel for compression ignition or diesel engines.

Diesohol

A blend of diesel fuel, hydrated ethanol and proprietary emulsifier.

Dual-fuel vehicle

Vehicle fitted with one engine and two fuel systems. The engine can operate on both fuels. An example is an LPG/Gasoline dual-fuel vehicle.

Embodied energy

The upstream processing energy required to produce an item. This term is widely used in life-cycle analysis

Exbodied emissions

emissions associated with the cumulative life-cycle of the fuel including its combustion.

Evaporative emission

Emission of hydrocarbons of a vehicle from sources other than the exhaust pipe.
Important sources are the venting of the fuel tank and the carburettor. Evaporative losses are subdivided into:
- running losses
- diurnal losses
- hot soak losses

FFV

Flexible-Fuelled Vehicle. Vehicle able to drive on any mixture of alcohol and gasoline up to 85% alcohol.

Formaldehyde

Aldehyde compound; HCHO; very toxic; probably carcinogenic.

IDI-engine

Indirect-Injection Engine; internal combustion engine (usually a diesel engine) with indirect fuel injection, for instance by way of a pre-combustion chamber or a swirl chamber.

Ignition delay

Expression usually used in connection with compression ignition engine, defined as the time between the start of the injection and the start of the ignition.

Lean mixture

mixture of air and fuel in a cylinder of a combustion engine containing less fuel than could be burnt by the oxygen present.

Liquefaction

The conversion of a gas to a fluid by lowering the temperature and or raising the pressure. LPG is a liquefied gas; natural gas and hydrogen are sometime liquefied.

Methylester

An ester which results from the esterification of oil with methanol, a known as biodiesel.

PAH

Polycyclic Aromatic Hydrocarbon(s). Aromatics of which the molecules contain several, linked benzene rings; in several cases carcinogenic.

PM10

Particulate matter with a size range (measured by the aerodynamic diameter) of less than 10 µm.

Pilot injection

method to ignite fuels that are difficult to ignite. A more easily ignitable fuel is injected into the engine, next to a amount of the real fuel. The added fuel will ignite first and subsequently ignite the real fuel. An example is diesel pilot injection in alcohol engines.

Reformulated fuel

A fuel (especially gasoline or diesel) blended to minimise undesirable exhaust and evaporative emissions.

Rich mixture

An air-fuel mixture in a combustion engine that contains more fuel than can be combusted by the air in the cylinder.

Spark ignition engine

Internal combustion engine with an ignition of the fuel/air mixture by means of a spark; also called otto engine.

Stoichiometric air/fuel ratio

The exact air/fuel ratio required to completely combust a fuel to water and CO_2.

Tailpipe emissions

Emissions of a combustion engine after the catalyst (as distinct from engine-out emissions which are measured before the catalytic converter).

Three-way catalyst

Catalytic reactor for combustion engines which oxidises volatile organic compounds (VOC) and CO, as well as reduces nitrogen oxides.

Vkm

vehicle kilometre

VOC

Volatile Organic Compound(s). Collective noun for hydrocarbons which are emitted in the volatile phase by vehicles. Usually described as HC-compounds.

Executive Summary

This report responds to a brief from the Australian Greenhouse Office to undertake:

- a comparison of road transport fuel emissions through a full fuel-cycle analysis of greenhouse gas emissions and emissions affecting air quality; and
- for each fuel, an assessment of current and near future (i.e., to 2006):
  - health-related issues (including occupational health and safety issues);
  - viability and functionality; and
  - environmental issues (including ecologically sustainable development) not related to greenhouse or air quality issues.

STRUCTURE

The report consists of three main parts. Part 1 consists of 15 chapters, each of which provides a *summary* of the salient points of each fuel, with a graphical representation of the emissions from the fuel, the reference fuel, and similar fuels, together with a representation of the uncertainty associated with the emissions. There is no summary description of low sulfur diesel because it is the reference fuel against which all subsequent heavy vehicle fuels are examined. The first chapter of Part 1 provides information on the background of the study.

Part 2 consists of *detailed* chapters on each fuel. These provide a literature review for each fuel, a description of the upstream and tailpipe emissions along with an explanation of the assumptions made in the quantitative modelling, the numerical results on which the graphical information in Part 1 is based, as well as the uncertainty estimates. In addition, each chapter provides details of the viability and functionality, health effects, environmental issues and expected future emissions associated with each fuel.

Part 3 consists of supporting chapters that discuss possible weighting methodologies for examining air quality emissions, and the modelling approach for the estimates of future emissions.

METHODOLOGY

Stakeholder consultation was an essential part of this study. Some ninety stakeholders were invited to comment on the study. These included fuel producers, vehicle manufacturers, government stakeholders, and environmental groups. Two stakeholder forums were held – one in Canberra and one in Melbourne – and these were followed by focussed roundtables for detailed discussion and comments on the exposure draft.

The study, completed over a five-month period from March to July 2001, consists of a literature review and a desk analysis of existing Australian and overseas studies that assess the emissions characteristics of 15 fuels. Three classes of emissions are considered: greenhouse gases, air pollutants, and air toxics. International tailpipe results were used to supplement the small amount of available local data on tailpipe emissions for the majority of the fuels studied. Substantial Australian data was available for calculating the upstream emissions of most of the fuels.

The study adheres to the international standards framework for conducting life-cycle analysis contained in the ISO14040 series (International Standards Organisation, 1998). A full life-cycle analysis of emissions takes into account not only direct emissions from vehicles but also those associated with the fuel's: extraction; production; transport; processing; conversion and distribution. Key issues addressed in the report include the system boundaries for the analysis, and the allocation of emissions for co-products, by-products and waste products.

Many of the feedstocks for fuels used in this study are either co-produced with other products or are from by-products and wastes from other production processes. Two options available for dealing with co-production are to split emissions between product streams - known as allocation - or to expand the study to take into account potential flow-on effects of providing a new use for the co-products and on systems currently using the co-products - known as system boundary expansion. The study follows the international standard on life-cycle assessment, which states that allocation should be avoided where possible. However alternative allocations have also been examined to determine whether there is a significant difference between the results.

SimaPro 5.0 life-cycle analysis software was used during the study. The software has an extensive Australian database of manufacturing energy input and emissions. Process trees outlining emissions from the production of fuels are produced by SimaPro and are included in the report. Other software packages are available but these are generally based on US emissions scenarios that are often not relevant to Australia. Further information about SimaPro is in Appendix 2.

Fuels are compared on the basis of both the mass of emissions per unit of energy used (g/MJ), and the mass of emissions per kilometre of distance travelled. The mass of emissions per kilometre travelled is the environmentally more meaningful figure, though it is subject to greater variability than the mass per unit energy. The mass of emissions per tonne-kilometre and the mass per passenger-kilometre are also calculated for trucks and buses respectively. Both upstream (pre-combustion) emissions and downstream (tailpipe, or combustion emissions) were considered. Emissions were also divided between those in urban and non-urban areas. We use the term “exbodied emissions” to refer to the cumulative upstream and downstream full fuel-cycle emissions.

The fuels examined were:

Diesel fuels: low sulfur (LS) diesel (the reference fuel for heavy vehicles), ultra-low sulfur (ULS) diesel, and Fischer-Tropsch diesel.

Biodiesel and canola oil: five upstream sources for biodiesel were examined, namely the crops: canola, soy, and rape; tallow and waste cooking oil. Tallow and waste cooking oil were treated both as waste products and as economic commodities.

Gaseous fuels: compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG) as autogas, and LPG as propane gas (HD5). Two modes of gas compression (gas and electric) were examined for CNG. Three modes of transport were examined for LNG.

Hydrated ethanol-based fuels: Diesohol, which is a blend of 15% ethanol with low sulfur diesel and an emulsifier (E15D), and hydrated ethanol produced by seven upstream processes.

Hydrogen.

Light vehicle fuels: Premium unleaded petrol (PULP), PULP blended with 10% anhydrous ethanol (E10P) and anhydrous ethanol blended with 15% PULP (E85P). Again, seven upstream ethanol production processes were examined.

LS diesel was chosen by the Australian Greenhouse Office as the reference fuel against which other fuels are compared because it will be the mandated diesel standard from 2002 to 2006 and Euro4 standard vehicles designed for ULS diesel will not achieve significant market penetration for some time after the introduction of ULS diesel. It is recognised that for some analyses a different reference fuel may be required. Data to facilitate such analyses is provided in Part 2 of this study.

Projections, based on a study commissioned by the European Commission Directorate-General for Energy, are made about the ability of vehicles using the different fuels to meet Australian Design Rules for vehicle emissions.

RESULTS

The results of the analysis are summarised in Table 1. This table is derived from data in Part 1 of this report, which in turn is derived from the information in Part 2 of the report. The structure of the results given in this report is:

- Executive summary – Table 1 summarises the material in Part 1.
- Part 1 – Bar charts (incorporating a measure of the uncertainty of the data) of Part 2 material.
- Part 2 – Detailed quantitative information in the form of tables and process trees.

The relative emissions performance of each fuel is determined using information in Part 2, which is analysed to determine whether the difference between LS diesel and each fuel is statistically significant.

The viability and functionality, and environmental issues relating to each fuel are mentioned in Table 1 only if there are issues to be noted. Thus, all fuels except canola oil are viable and functional. Noteworthy environmental and ecologically sustainable development issues are referred to if they have a significant impact on the analysis of the fuel. For example, biodiesel made from tallow has to allow for significant methane emissions from the upstream beef cattle industry. In addition, ethanol made via ethylene from a fossil fuel emits large quantities of greenhouse gases because the ethanol is no longer from a renewable fuel.

The last column of Table 1 uses the estimates of Arcoumanis (2000) developed for the European Auto-Oil II program to determine the likelihood of the fuel meeting future Australian Design Rule emission limits. As the future Australian Design Rule emission limits are based on the European standards, the comparison is given against Euro3 and Euro4. These results indicate that some ethanol-based fuels may have difficulty meeting Euro3 and Euro4 limits for total hydrocarbons, and that 100% biodiesel may have difficulty meeting Euro 3 limits for particulate matter (PM), but improvements in vehicle technology are expected to enable 100% biodiesel to meet Euro 4 limits for particulate matter. Arcoumanis notes that a blend of 20% - 30% biodiesel with diesel in heavy vehicles is expected to meet all Euro 4 standards. With respect to diesohol, the higher THC and CO emissions reflected in the Arcoumanis' report can be overcome according to APACE Research. Consequently diesohol made from low sulfur diesel should be able to meet all future ADRs.

The heavy vehicle fuel results from Table 1 are summarised below:

Diesel fuels

The removal of sulfur from diesel produces a fuel that emits less important criteria pollutants and air toxics. Tailpipe emissions of particulate matter and hydrocarbons from ULS diesel are less than LS diesel, and emissions of these pollutants from Fischer-Tropsch diesel are less than those from ULS diesel. Tailpipe emissions of NOx for Fischer-Tropsch diesel and ULS diesel are similar to each other but are less than LS diesel.

The greater processing energy involved in the removal of the sulfur means that exbodied greenhouse gas emissions are similar for LS diesel and ULS diesel, but higher in the case of Fischer-Tropsch diesel.

Lower sulfur fuels permit more efficient operation of emission control devices such as exhaust gas recirculation, oxidation catalysts, and particulate traps. Consequently the use of ULS diesel (50ppm sulfur) will lead to improved performance of these devices when compared with LS diesel, and Fischer-Tropsch diesel with a very low sulfur content will perform better than ULS diesel.

A significant advantage for the ULS diesel and Fischer-Tropsch diesel is that they can be used by current refuelling infrastructure and in existing engines.

It is to be expected that once diesel vehicles routinely use ultra-low sulfur fuels and are equipped with such emission control devices then they will meet Euro4 standards.

There are no operational Australian gas to liquids plants producing Fischer-Tropsch diesel and so data from overseas plants has been considered in the course of this study. One issue raised in the course of the study was the energy source for the production of Fischer-Tropsch diesel. About 70% of energy is assumed to be derived from natural gas and the remainder from hydrogen produced in the gas shift reaction used as part of the Fischer-Tropsch process. A review should be undertaken when information about emissions from the production of Fischer-Tropsch diesel in Australia becomes available.

Biodiesel and canola oil

Canola oil is not presently a viable heavy vehicle fuel. Major alterations to heavy vehicle engines are needed to make it a viable fuel.

All forms of biodiesel are more climate-friendly than diesel. In other words, biodiesel emits less exbodied greenhouse gases than diesel. The emissions involved in upstream activities for biodiesel are less than the emissions involved in diesel combustion and upstream activities. Biodiesel made from tallow is less climate-friendly (i.e. it emits more exbodied greenhouse gases) than biodiesel made from vegetable oil because of the upstream methane emissions from cattle.

As in the case of ethanol, biodiesel made from a waste product has lower emissions than the same fuel made with a product that has to be purchased. This comes about because the rules associated with life cycle analysis specify that in such situations the upstream emissions in generating the waste product do not have to be debited to the final product. Biodiesel made with waste cooking oil is thus the best form of biodiesel on a life-cycle basis.

Biodiesel made from vegetable oils is comparable to diesel in its exbodied emissions except for oxides of nitrogen and particulate matter. Provided that the emissions from diesel-operated agricultural machinery are properly controlled then exbodied emissions of particulate matter from biodiesel are lower than those of diesel. However, it appears that exbodied emissions of NOx from biodiesel are higher than those of diesel. The major disadvantage of 100% biodiesel is related to concerns about its ability to meet Euro3 standards for PM, and to meet both Euro3 and Euro4 standards for NOx.

The growth of crops for biofuels should be monitored to ensure that principles of ecologically sustainable development are upheld.

Gaseous fuels (Natural Gas - Dedicated OEM)

There have been major advances in natural gas engines in recent years that mean that the present generation of natural gas vehicles have significantly lower emissions than the present generation of diesel vehicles such that some of the present generation of natural gas engines can already meet Euro4 standards. The emissions based on use in original equipment manufacture (OEM) vehicles are lower in all categories – greenhouse gases, important criteria pollutants, and air toxics. The lower particulate emissions and noise levels compared with diesel make it particularly attractive for urban areas.

The major uncertainty relates to leakage. There are many studies, based on earlier estimates of upstream and in-service methane leakage, which claim that natural gas vehicles emit more greenhouse gases than conventional fuel heavy vehicles. Based on our analysis of present day vehicles we believe that upstream and in-service leakage has been sufficiently reduced that the present generation of OEM natural gas vehicles have lower exbodied greenhouse gas emissions than the equivalent diesel vehicles.

This study used a value of 0.1% for fugitive emissions from distribution and compression, which is based on information provided by stakeholders. If Australian fugitive emissions were to be significantly higher (at approximately 4%) then the full fuel-cycle greenhouse gas emissions from CNG and LNG would exceed those from diesel.

Table 1
Summary of the results of the analysis per tonne-kilometre and per passenger-kilometre

Fuels	GHG	PM	NOx	Toxics[1]	Health	V&F	ESD	Future ADR
LS diesel (Aus)	Reference fuel for heavy vehicles							
ULS diesel (Aus)	=	~	~	~	√			
ULS diesel (100% hydroprocessing)	=	~	~	~	√			
Fischer-Tropsch diesel	+	-	=	-	√			
100% Biodiesel (canola)	- -	~	+	=	=			PM>E3; NOx>E3,E4
100% Biodiesel (soybean)	- -	~	+	=	=			PM>E3; NOx>E3,E4
100% Biodiesel (rape)	- -	~	+	=	=			PM>E3; NOx>E3,E4
100% Biodiesel (tallow-expanded sys. boundary)	- -	~	+	=	=		{CH_4	PM>E3; NOx>E3,E4
100% Biodiesel (tallow-eco.allocat.)	- -	~	+	- -	√		{upstream	PM>E3; NOx>E3,E4
100% Biodiesel (waste oil)	- -	~	+	- -	√			PM>E3; NOx>E3,E4
100% Biodiesel (waste oil 10% original oil value)	- -	~	+	- -	√			PM>E3; NOx>E3,E4
Canola			No data			XX		
[2]CNG (Electric compression)	- -	- -	- -	- -	√			
[2]CNG (NG compression)	- -	- -	- -	- -	√			
[2]LNG (from existing pipeline)	- -	- -	- -	- -	√			
[2]LNG (Shipped from north west shelf)	- -	- -	- -	- -	√			
[2]LNG (Road transport to Perth)	- -	- -	- -	- -	√			
[2]LPG (Autogas)	-	- -	- -	-	√			
[2]LPG (HD5)	-	- -	- -	-	√			
LSdiesohol	~	~	=	=	=			??THC>E3,E4
Ethanol azeotropic (molasses-expanded sys.bound.)	- -	-	=	-	√			THC>E3,E4
Ethanol azeotropic (molasses-economic allocation)	~	-	~	-	√			THC>E3,E4
Ethanol azeotropic (wheat starch waste)	- -	=	~	-	=			THC>E3,E4
Ethanol azeotropic (wheat)	-	=	=	=	=			THC>E3,E4
Ethanol azeotropic (wheat) fired with wheat straw	- -	+	=	++	X			THC>E3,E4
Ethanol azeotropic (woodwaste)	- -	=	-	++	X			THC>E3,E4
Ethanol azeotropic (ethylene)	+	-	=	++	X		fossil-fuel based	THC>E3,E4
Hydrogen (from natural gas)-upstream only	=	- -	- -	- -	√			
PULP	Reference fuel for light vehicles							
PULP e10 (molasses-exp.sys.bound.)	=	=	=	=	=			
PULP e10 (molasses-eco.allocat.)	=	=	=	=	=			
PULP e10 (wheat starch waste)	=	=	=	=	=			
PULP e10 (wheat)	=	=	=	=	=			
PULP e10 (wheat WS)	=	=	=	=	=			
PULP e10 (wood waste)	=	=	=	=	=			
PULP e10 (ethylene)	=	=	=	=	=			
PULP e85 (molasses-exp.sys.bound.)	- -	=	=	=	=			THC>E3,E4
PULP e85 (molasses-eco.allocat.)	-	=	=	=	=			THC>E3,E4
PULP e85 (wheat starch waste)	- -	=	=	=	=			THC>E3,E4
PULP e85 (wheat)	-	=	++	=	=			THC>E3,E4
PULP e85 (wheat WS)	- -	+	++	++	X			THC>E3,E4
PULP e85 (wood waste)	- -	=	-	++	X			THC>E3,E4
PULP e85 (ethylene)	++	=	++	++	X		fossil-fuel based	THC>E3,E4

GHG: greenhouse gases; PM: particulate matter; NOx: oxides of nitrogen; V&F: viability and functionality; ESD: ecologically sustainable development.

Symbols: - -, significantly lower (than the reference fuel); -, lower; ~, slightly lower; =, much the same; +, higher; and ++, significantly higher. Health effects are based on the rankings for toxics and PM. √ indicates improvement (compared with the reference fuel); X, worse. The symbol XX indicates very poor.

Significantly lower/higher means two standard deviations difference; higher/lower means more than one standard deviation difference.

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[1] Due to limited air toxics data THC was used as a proxy. Thus these results are only a rough guide.

[2] CNG, LNG and LPG results apply only to OEM dedicated gas vehicles.

The major disadvantages of natural gas are the lack of sufficient refuelling stations, and the perceptions of safety problems that arose from fires in improperly maintained earlier generation natural gas vehicles. The extra weight of CNG fuel tanks leads to slightly higher fuel consumption, or loss of payload in the case of buses. This is less of a problem with LNG vehicles due to the higher energy density.

Gaseous vehicles (LPG - dedicated OEM)
A dedicated LPG bus produces significantly lower emissions of important criteria pollutants, and lower exbodied emissions of greenhouse gases. Air toxics from tailpipe emissions of LPG vehicles are much lower than those of diesel vehicles, but the greater upstream emissions of air toxics results in the exbodied emissions of air toxics from LPG being much the same as those from diesel.

LPG HD5 has minimum propane content of 90% whereas the ratio of propane and butane varies widely in autogas LPG. When compared with autogas, HD5 LPG emits more NOx but less particulate matter. Emissions of hydrocarbons are similar. The main benefit of HD5 compared with autogas is that the compression ratio can be altered to suit this higher-octane fuel.

The lower particulate emissions and lower noise levels compared with diesel make it attractive for use in urban areas.

The major disadvantage of LPG is the lack of market penetration of dedicated heavy LPG vehicles.

Gaseous vehicles (Converted vehicles and dual fuel)
The emissions performance of converted Australian CNG vehicles is known to be significantly worse than OEM CNG vehicles. However there is little data on CNG conversion configurations that are currently available. It is possible that the difference in emission levels between converted vehicles and OEMs will decrease as the heavy-duty vehicle conversion industry becomes more firmly established.

Diesel vehicles converted to LPG are less successful at reducing tailpipe emissions than OEM LPG vehicles. At best one could consider converted LPG vehicles as equal to their diesel counterparts except for HC, which appears to be higher, and PM, which remains significantly lower. The Australian LPG conversion industry for heavy vehicles is at an early stage in its development and the data available, from only two tests, may not reflect the emissions performance of converted vehicles in the longer term.

Hydrated ethanol based fuels
The nature of the upstream feedstock for the production of ethanol is crucial in determining whether ethanol-based fuels are superior or inferior to diesel regarding greenhouse gas emissions.

The use of renewable feed-stocks such as molasses, wheat, or wheat starch appears to produce lower exbodied emissions of greenhouse gases and emissions affecting air quality than LS diesel provided that wheat straw is not used as the energy source in which case there are increased emissions of hydrocarbons and possibly air toxics, as is also the case with the use of woodwaste. The growth of crops for biofuels should be monitored to ensure that principles of ecologically sustainable development are upheld.

Ethanol made from a non-renewable source via ethylene produces greater exbodied emissions of greenhouse gases than diesel fuel.

The major disadvantage of ethanol is that present estimates indicate that it may have difficulty meeting Euro3 and Euro4 standards in relation to the emissions of hydrocarbons.

In the case of diesohol, the manufacturers are confident that a combination of cetane improver and fuel injection modifications (to avoid vapour locks) will enable diesohol to meet Euro3 and Euro4 standards for hydrocarbons and carbon monoxide. Table 1 indicates that greenhouse emissions and particulate matter from diesohol are slightly lower than LS diesel. NOx and emissions of air toxics are similar to LS diesel. Benzene levels should decrease when ethanol concentrations increase which means that tailpipe emissions for these air toxics should be lower. Acetaldehyde and formaldehyde emissions will increase. Special measures are needed to control evaporative emissions from vehicles using alcohol fuels.

Hydrogen

Hydrogen fuel cells offer the possibility of offering significant potential improvements in emissions. Due to the experimental nature of this technology little is known of the in-service performance but there are assumed to be no tailpipe emissions apart from water vapour. The operation of three fuel cell buses in Perth by late 2002 will provide such information. It is known that hydrogen fuel cells are currently very expensive and very heavy in terms of weight per kilowatt output.

Hydrogen manufactured using natural gas is very energy intensive and lifecycle emissions are similar to those of LS diesel. Production of hydrogen by low-pressure water electrolysis would be an ecologically sustainable method of production provided that the electricity used to undertake electrolysis is based on renewable energy.

Light vehicle fuels

The addition of 10% ethanol to premium unleaded petrol to produce petrohol does not significantly alter the emission characteristics of the petrol, especially when the uncertainties and the variability of emission estimates are taken into account. Higher evaporative emissions may present problems with petrol/ethanol blends.

In an E85 blend of 15% petrol and 85% ethanol, the use of anhydrous ethanol (less than 1% water by volume) from a renewable source significantly reduces exbodied greenhouse gas emissions, as may be expected. However, there are doubts about the ability of 85% ethanol used in light vehicles to meet Euro3 and Euro4 emission standards for hydrocarbons.

Ethanol fuels made from a fossil fuel, such as ethylene, have higher exbodied emissions (than from premium unleaded petrol) for greenhouse gases, important criteria pollutants, and air toxics with one exception (aldehydes). The exbodied emissions of particulate matter are reduced.

UNCERTAINTIES

This study compares fuels on a statistical basis using the mean value and standard deviation for each fuel to address the variability present in emissions data. Uncertainties are calculated for each fuel by emission type. The smallest uncertainties for tailpipe emissions are associated with carbon dioxide followed by hydrocarbons, oxides of nitrogen, carbon monoxide and particulate matter. Standard deviations for each fuel are provided in each chapter in Part 2 of the report.

The use of the standard deviation in Table 1 minimises the impact of statistical variation inherent in emissions data and provides a greater level of confidence in the findings. The use of the terms significantly higher or lower in Table 1 refers to a two standard deviation difference. Higher or lower, as expressed by – or + signs, refers to one standard deviation difference. In some cases emissions data have a difference of less than one standard deviation but it is clear that the emissions are consistently less than those of low sulfur diesel. In this case a tilde sign "~" has been used in Table 1.

RECOMMENDATIONS

Insufficient is known about the emissions of air toxics from vehicles, and the appropriate Australian risk-weighted factors to use in examining their relative effects. It is expected that these issues will be examined as part of the work on a National Environment Protection Measure (NEPM) on air toxics.

When the NEPM work on air toxics is finalised, the air toxics issues examined in this report should be reviewed.

The sensitivity analysis revealed the importance of fugitive emissions in determining whether CNG and LNG are more, or less, climate friendly than diesel fuel. We recommend a study be conducted that combines measurement with an audit of fuel use to determine the level of fugitive emissions

Many of the gaseous fuel vehicles to be used in Australia are likely to be converted vehicles or dual fuel vehicles. Consequently it is important to ensure that the emissions from such vehicles are no worse than those of the unconverted vehicle. The collection and collation of emissions information from such vehicles needs to be systematically undertaken.

It follows that if the data produced herein are to be used in guiding initiatives that lead to alternative fuels implementation, the data should be reviewed periodically in two ways.

Firstly, an analysis such as the one in this report has a limited life. In some cases (such as hydrogen and Fisher-Tropsch diesel) there are no operational plants producing transport fuels presently in existence in Australia. Because it is to be expected that operational plants will be in place within a few years, the study will need to be repeated such that a re-analysis focuses on production processes that are actually in place at the time of the re-analysis.

Secondly, validation of the values established here through experimental tests would ensure that the technology being used in Australia is recognised in the allocation of environmental benefits accruing from the use of alternative fuels. A measurement program that surveys a significant proportion of alternative fuel vehicles should be undertaken in order to support this recommendation. Such an experimental program should ensure that the vehicles that are tested vary with engine and vehicle type; and the emission results are compared with the existing SAE-A truck fuel consumption model as described in Part 3 of this report.

1. Background

1.1 Introduction

This report responds to a brief from the Australian Greenhouse Office (AGO) to undertake:

- a comparison of road transport fuel emissions through a full fuel-cycle analysis of greenhouse gas emissions and emissions affecting air quality; and
- for each fuel, an assessment of current and near future (i.e., to 2006):
    - viability and functionality;
    - health related issues (including occupational health and safety issues); and
    - environmental issues (including ecologically sustainable development) not related to greenhouse or air quality issues.

The full Terms of Reference are given in Appendix 1.

Information in this report may be used by the Australian Greenhouse Office when considering the appropriateness of recommending the inclusion of additional fuels under the Diesel and Alternative Fuels Grants Scheme. Thus, it incorporates a desk study and literature review of existing Australian and overseas data concerning the emissions characteristics of alternative and conventional fuels that are or may be suitable for use in road vehicles weighing 4.5 tonnes gross vehicle mass (GVM) or more. The Prime Minister indicated under the *Measures for a Better Environment* Statement of May 1999 that the Chief Executive of the AGO may certify additional fuels under the DAFGS. The scheme is designed to maintain price relativity as at 1 July 2000 between diesel and alternative fuels so as not to discourage the use of cleaner fuels.

The AGO requires an analysis that will:

- conduct a full fuel-cycle analysis of emissions for on-road transport fuels;
- determine whether any fuel has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period to 2006 (inclusive);
- examine the viability and functionality of the fuels;
- examine significant health (and occupational health and safety) related issues from the use of the fuels; and
- examine other significant environmental issues resulting from the use of the fuels including ecologically sustainable development.

These points broadly cover the criteria for determining the appropriateness of certifying a new fuel under the DAFGS.

1.1.1 Approach

This study consists of a literature review and a desk analysis of existing Australian and overseas studies that assess the emissions characteristics of fifteen fuels. Three classes of emissions are considered:

- Greenhouse gases, which comprise carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons.
- Air pollutants, which comprise carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic volatile organic compounds, and particles.
- Air toxics, which include compounds such as benzene, aldehydes (formaldehyde and acetaldehyde), 1,3 butadiene, polycyclic aromatic hydrocarbons (PAH), toluene, and xylene.

This study was completed over a five month period from March to July 2001.

1.1.2 Previous Work

This study extends the work undertaken by Beer et al. (2000) in their life-cycle emissions analysis of alternative fuels for heavy vehicles. It does so, with a focus on the Australian context, by i) examining more recent investigations and incorporating their data, if relevant, ii) examining some new fuels that were not examined in the earlier study, and iii) examining more upstream pathways for fuels that were examined in the earlier study.

1.2 Life-Cycle Analysis (LCA)

A general introduction to life-cycle analysis may be found in Graedel & Allenby (1995), while the international standards on LCA, contained in the 14040 series (International Standards Organisation, 1998) provide a basic framework in which to undertake LCA. When LCA is applied to the emissions from the use of different transport fuels, both combustion and evaporative emissions need to be included, as well as the full life cycle of the fuel. A full life-cycle analysis of emissions takes into account not only the direct emissions from vehicles (which are referred to as downstream emissions) but also those associated with the fuel's:

- Extraction
- Production
- Transport
- Processing
- Conversion
- Distribution

These are referred to as upstream emissions. In the context of automobile fuels they are also referred to as pre-combustion emissions.

The Bureau of Transport and Communications Economics (1994) uses the term 'full fuel cycle' for the situation that takes into account emissions from all energy used in achieving a given transport task with a particular fuel. The full fuel cycle contrasts with the more basic analysis of tailpipe emissions.. A life-cycle basis for estimating fuel emissions for a particular fuel takes into account emissions in vehicle manufacture and vehicle life, whereas a full life-cycle analysis sets the system boundaries much wider and incorporates emissions from the associated infrastructure. The term 'well to wheel emissions' is also used in the analysis of automotive fuels.

Life-cycle analysis is often used to determine the amount of upstream energy used to construct a particular object. The term 'embodied energy' has achieved widespread use to denote such energy. However, the term 'embodied emissions', to cover the full fuel-cycle emissions of gases or pollutants, would be a misnomer, because emissions are emitted, not embodied. Thus, in this report, we use the term exbodied emissions to refer to the cumulative life cycle of emissions (including combustion) associated with a fuel.

Emissions related to vehicle manufacture, maintenance and disposal, and road building are relevant to total transport emissions, but they are not likely to vary significantly with the nature of the fuel used. The infrastructure associated with refuelling will, however, vary with the different alternative fuels.

1.2.1 System Boundary for LCA

Some elements of the production system are excluded from the study, for two reasons:

- the process is considered small enough to ignore, given the aims of the study; and

- the impacts of the process belong to a different product system entirely, which is the case with waste products which attract little or no revenue in their disposal.

Figure 1.1 shows a simplified outline of the system elements for the fuels studied, and places a boundary around those included in the study. Capital equipment and infrastructure are universally excluded from the study, based on its expected low contribution to the overall environmental impact of the fuel used. The impacts derived from capital goods are expected to be similar for each of the fuels studied. Though the capital goods in fuels delivery and filling could have substantial impacts if a radically different filling infrastructure is required, the full context of the market segment and expected market penetration of the fuel would need to be known to determine this impact. These factors are beyond the scope of the study so the filling infrastructure has also been excluded from quantitative calculations.

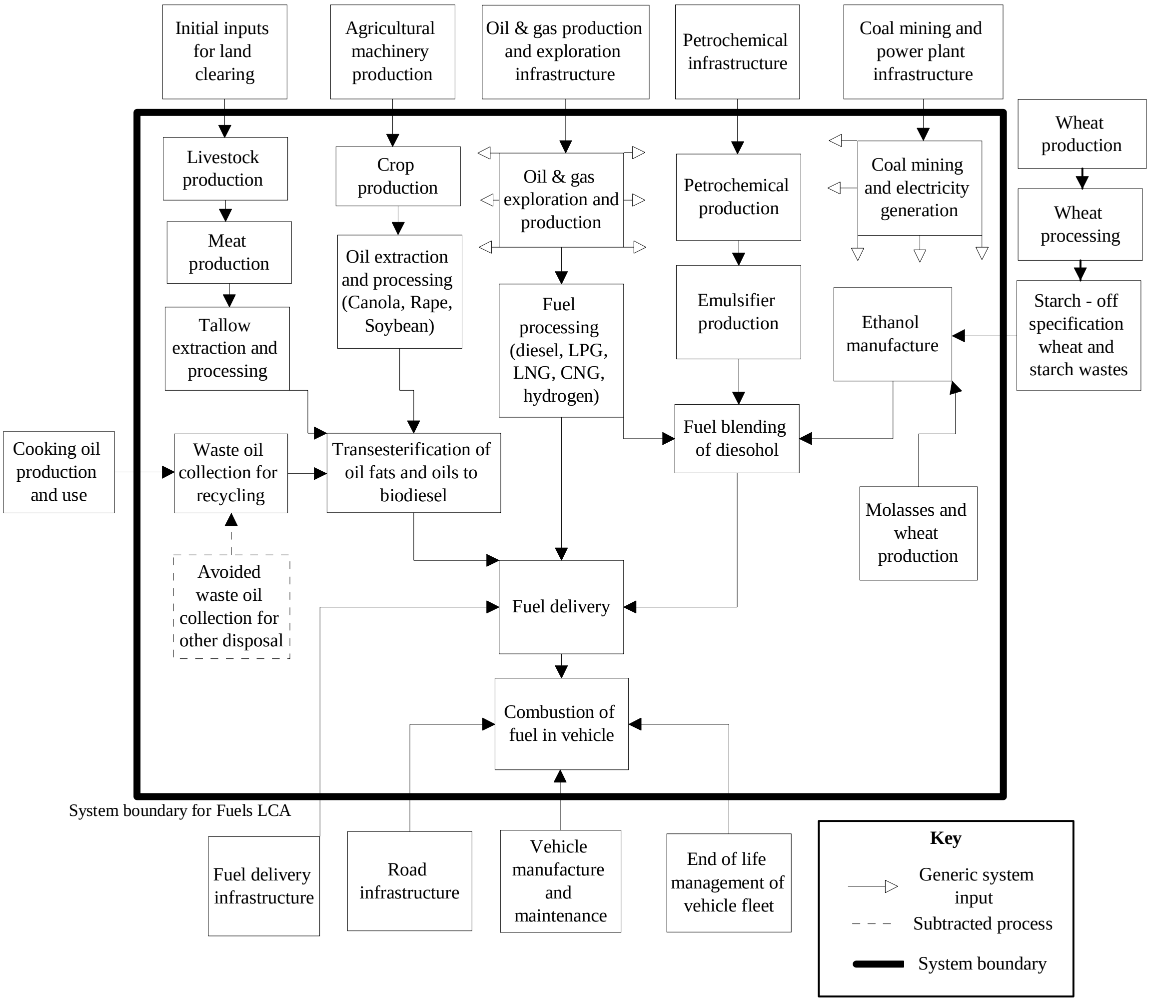

Figure 1.1
System boundaries in fuels LCA – note not all fuels studied are included in diagram and different allocation procedures have been employed for individual fuels – see fuel chapters for full details.

When considered as waste products, waste cooking oil and waste wheat products are outside the system boundary due to their low value as a waste product. Should these wastes gain in value as demand increases then an alternative approach is required, that is depicted in subsequent calculations as an alternative allocation abbreviated as alt. alloc.

Allocation of burdens for co-products and by-products

Many of the feedstocks for fuels used in this study are either co-produced with other products or are from by-products and wastes from other production processes. A methodology needs to be applied to determine the appropriate environmental impacts of these co-produced materials. The two main options available for dealing with co-production are to split emissions between the product streams – known as allocation, or to expand the study to take account of the potential flow-on effects of providing a new use for the co-product, on systems currently using the co-product, which is known as system boundary expansion. The two basic approaches are shown in Figure 1.2.

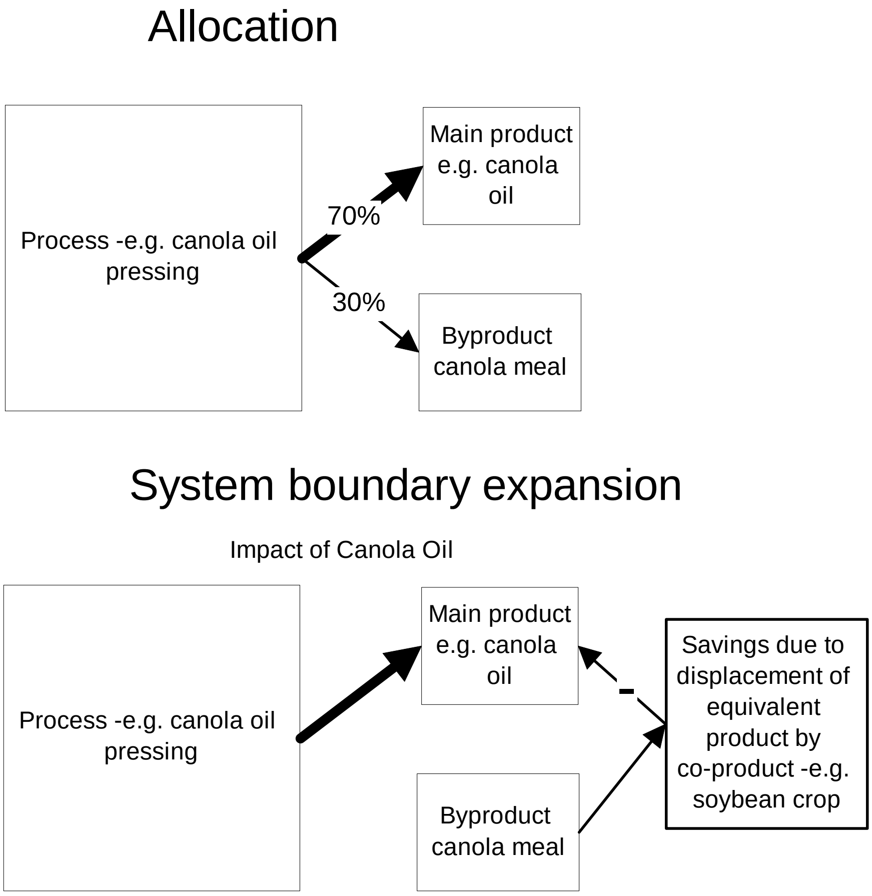

Figure 1.2
Approaches to allocation in life-cycle analysis

The international standard on life cycle assessment (International Standards Organisation, 1997) states that allocation should be avoided where possible through the use of system boundary expansion. Where this is not possible allocation should be undertaken using either causal relationships, based on economic, or physical properties of the co-products.

The problem with system boundary expansion is that it requires a good knowledge of the market forces that result in the product substitution. It is also complicated by the factor that many co-products are competing with other co-products, so expanding the system boundary for canola meal may find that soy meal is the likely replacement material. This product has the same allocation issues as canola meal. It is necessary then to follow the product substitution chain back to a point where a "determining" or "main" product is found which can expand or contract its production in line with system dynamics. This is different to by-products which are assumed to be able only to alter the market in which they are utilised and the level of utilisation.

Weidema (1999) has developed four simple rules for determining expanded system boundary allocation based on the level of utilisation of the by-product (or waste).

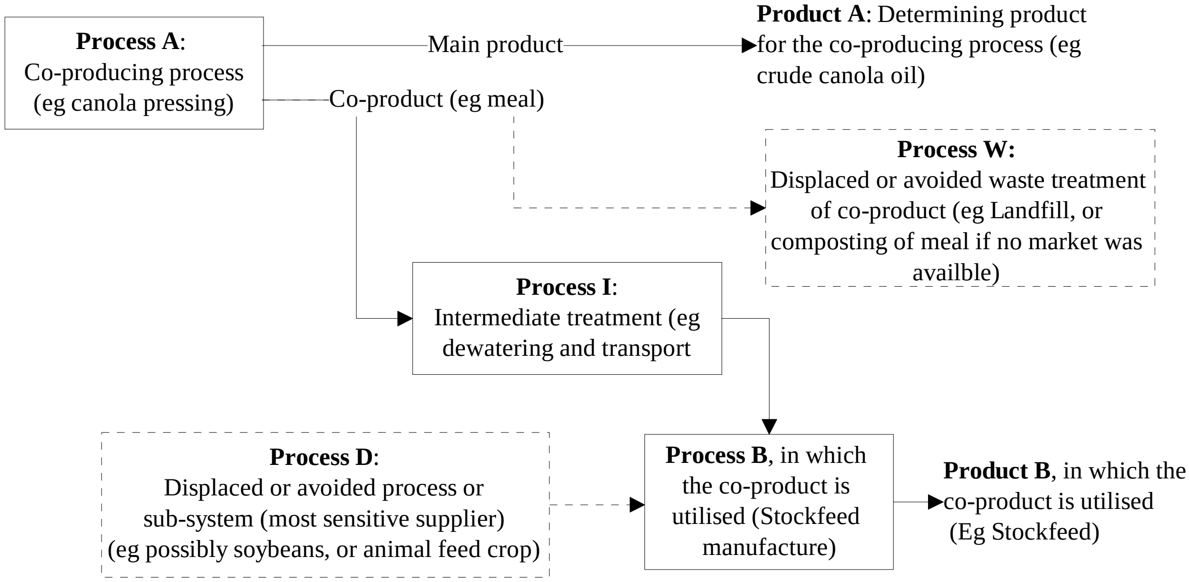

Figure 1.3
Model for system boundary expansion – Adapted from (Weidema, 1999)

Using the model of Figure 1.3 for reference Weidema (1999) developed the following four rules for ascribing process impact to different products. These are:

1)*"The co-producing process shall be ascribed fully (100%) to the determining product for this process (product A)"* (eg all impact of canola growing and crushing ascribed to the canola crude oil).

2)*"Under the conditions that the non-determining co-products are fully utilised in other processes and actually displace other products there, product A shall be credited for the processes, which are displaced by the other co-products, while the intermediate treatment (and other possible changes in the further life cycles in which the co-products are used, which are a consequence of differences in the co-products and the displaced products) shall be ascribed to product A"* (eg crude canola oil is given credit for avoided soybean production (or other equivalent crop) but also bears the impacts of dewatering and transporting the meal to the stockfeed production process).

If the two conditions stated in rule no. 2 are not fulfilled, rule no. 3 and 4 apply, respectively:

3)*"When a non-determining co-product is not utilised fully (i.e. when part of it must be regarded as a waste), but at least partly displaces another product, the intermediate treatment shall be ascribed to product B, while product B is credited for the avoided waste treatment of the co-product"* (eg if canola meal was not fully utilised and some of it was being landfilled for want of a market, then the dewatering and transport would be part of the stock feed life cycle, but the stockfeed life cycle in turn receives credits for avoided landfill impacts from landfilling of the canola meal). Crude canola oil is given all impacts of production and landfilling of the meal (as any increase in production will probably have 100% of meal to landfill as the market for meal is saturated under this scenario.)

4) “*When a non-determining co-product is not displacing other products, all processes in the entire life cycle of the co-product shall be fully ascribed to product A*” (eg if the canola meal is applied to land, but provided little value and does not displace fertiliser use, all the impacts are ascribed to crude canola oil and no credits are given).

In this study system boundary expansion has been used wherever the fuel is produced from the non-determining co-product (molasses, LPG and tallow). In three instances co-products have been considered so close to waste that no prior emissions have been allocated (forest waste, starch waste in diesohol, and waste oil). Where a determining product is used as a fuel such as for canola, rape and soybean crops, economic allocation was applied due to difficulties and additional work in applying expanded system boundaries.

Compliance with ISO14040 series standard on Life-Cycle Assessment

In general the methodologies applied in this study are in compliance with the ISO 14040 series standards[1]. In particular we have endeavoured to follow the standard on the following points:

Allocation procedures: For multi-product systems we have opted first to try expanding the system boundary to eliminate the need for allocation. Where this has not been practical, allocations have been made on energy content (e.g. in refineries) or economic value (e.g. agricultural products). Sensitivity studies have been undertaken using alternative allocation procedures where there is some question over the appropriateness of the allocation procedure and where an alternative method is possible.

Indicators: The two main indicators being examined in the project are global warming and air quality. In the case of comparative assertions released to the public, the standard allows for calculation of indicator results (characterisations) that are internationally accepted. The greenhouse indicator is clearly internationally accepted, with the characterisation factors[2] being developed by the IPCC. For the air quality indicator, the use of such an indicator is not uncommon internationally. However, international acceptance of the characterisation factors that are used is unlikely given the local nature of the air quality impacts and the fact that the values are based on this local situation. Compliance on this point is unclear.

Peer review: The project has had three types of peer review: an internal peer review process within CSIRO, review by the Australian Greenhouse Office as the commissioner of the study, and stakeholder review through a stakeholder forum held on 7 June, and subsequent focussed roundtables on 25 June and 26 June. During July 2001 Australian Government stakeholders reviewed the draft report, and their input was incorporated into the final report.

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[1] The series include ISO 14040 (International Standards Organisation, 1997) giving a general framework, ISO 14041(International Standards Organisation, 1998) which outline inventory assessment, ISO 14042 (International Standards Organisation, 2001) which outlines impact assessment and ISO14043 (International Standards Organisation, 2001) which outlines interpretation.

[2] The characterisation factors are considered in this report to be part of the third mandatory stage of impact assessment [see page 3 of International Standards Organisation, 2001a] as they apply to one damage endpoint — human health effects from urban air pollution. The values could be considered as weighting factors and thus part of impact weighting [stage three of the optional impact assessment process, which is not allowed by the standard in the case of a comparative assertion released to the public.]

Recent life-cycle studies of fuels or transport

The earlier report of Beer et al. (2000) reviewed the detailed studies of Sheehan et al. (1998) on the life-cycle of biodiesel in an urban bus, and of Wang and Huang (1999) who examined the full fuel cycle of natural gas, as well as the European IEA/AFIS work. The Flemish research organisation VITO undertook a comparative life-cycle assessment of biodiesel in Europe (Ceuterick and Sprinckx, 1999). There are a number of life cycle analyses of individual fuels that are reviewed or referenced in the appropriate chapters.

MacLean et al. (2000) used US information to examine the life-cycle emissions of alternative fuels when used in petrol-driven vehicles.

1.2.2 Life-Cycle Analysis Modelling

Life-cycle analysis was done using SimaPro 5.0 software. SimaPro 5.0 is an open structure program that can be used for different types of life-cycle assessments. The production stage, the use stage and the end-of-life scenario can be specified in as much detail as necessary by selecting processes from the database and by building process trees, which can be drawn by the program. The results are presented in scores or graphs, varying from a list of substances (inputs and outputs), characterised scores, normalised scores or evaluated scores.

An alternative life-cycle model for alternative fuels, much used in the United States, is the GREET model developed at Argonne National Laboratories. Appendix 2 compares GREET and SimaPro, and provides an explanation of the structure of SimaPro process trees.

1.3 Structure of the Report

This report examines the alternative fuels with respect to their life-cycle emissions of greenhouse gases and air pollutants. Each fuel is considered in a separate chapter that examines: Full Fuel-Cycle Analysis; Viability and Functionality; Health Issues; and Environmental Impact and Benefits. Wherever possible the emissions are provided on a quantitative basis as a result of values available in the literature.

The report consists of three main parts. Part 1 consists of 15 chapters, each of which provides a *summary* of the salient points of each fuel, with a graphical representation of the emissions from the fuel, the reference fuel, and similar fuels, together with a representation of the uncertainty associated with the emissions. There is no summary description of Low Sulfur Diesel because it is the reference fuel against which all subsequent heavy vehicle fuels are examined.

Part 2 consists of *detailed* chapters on each fuel. These provide a literature review for each fuel, a description of the upstream and tailpipe emissions along with an explanation of the assumptions made in the quantitative modelling, the numerical results on which the graphical information in Part 1 is based as well as the uncertainty estimates. In addition, each chapter provides details of the viability and functionality, health effects, environmental issues and expected future emissions associated with each fuel.

Part 3 consists of supporting chapters that discuss possible weighting methodologies for examining air quality emissions, and the modelling approach for the estimates of future emissions.

We have used a hierarchy of data quality to assess the data on emission profiles from different vehicle types. Australian experimental data on emissions from heavy vehicles is used wherever possible. Recent overseas data on heavy vehicles is reviewed and, where appropriate, used in the SimaPro model.

The comparison between different fuels is done on the basis of both the mass of emissions per energy used (g/MJ), and the mass of emissions per kilometre of distance travelled. The mass of emissions per kilometre travelled is the environmentally most meaningful figure, though it is subject to greater variability than the mass per unit energy. Arriving at the emissions per kilometre involves three steps:

Life-Cycle Analysis of Emissions

This first step produces an estimate of the greenhouse gas and air quality emissions from each fuel expressed as the mass of emissions per unit of energy - kg/MJ.

Fuel combustion

This characterises the fuel in terms of its energy per unit volume in units of MJ/L

Performance

This characterises the fuel in terms of the per-kilometre emissions.

An alternative way of examining this is to examine the units associated with the quantities:

g/km = (g/kWh)x (1/engine efficiency) x (kWh/MJ) x (MJ/kg) x (kg/L) x (L/km).

The first term (g/km) is the final performance result that this report examines. The emissions are expressed on a per kilometre basis. One arrives at this by considering the product of the engine emissions (g/kWh), the fuel combustion characteristics (MJ/kg), the fuel density (kg/L) and the vehicle fuel economy (L/km). Each one of these four terms will display variability, so that the uncertainty associated with the emissions will be the sum of the percentage uncertainties associated with each of the four terms.

We have retained the use of g/kWh (even though it is dimensionally equivalent to g/MJ) to emphasise that the output of an engine dynamometer refers to the usable work, rather than the energy content of the fuel. The theoretical Carnot efficiency of a diesel engine is 64%, though the efficiencies of actual diesel engines are lower.

Whereas the first four steps given above can be undertaken on the basis of static tests of motors and theoretical calculations on fuel properties, performance is determined in this study on the basis of fuel economy, expressed in units of L/km. Ideally this is based on road tests using vehicles with alternative fuels. Such road tests are very difficult and expensive to carry out so that most emission tests are actually carried out either as static tests or on a chassis dynamometer.

Static tests require the engine to be removed from the chassis, and then tested over a lengthy test protocol. Chassis dynamometer tests involve the drive wheels of the vehicle being placed over a set of rollers, and the vehicle being driven in a representative test cycle while the emissions are collected and then analysed. The dynamometer must have sufficient rotating inertia to simulate the mass of the vehicle in acceleration and deceleration manoeuvres. Most tests are performed on unladen vehicles because of limited dynamometer inertia.

Fuels will be presented in terms of emissions per tonne-km in the case of trucks, and emissions per passenger-km in the case of buses. Presentation in this form will minimise the variations in emissions that arise from payload variations, rather than fuel variations. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116). Adjustments, such as those due to the extra weight of CNG tanks, have been made to these figures in some situations.

The quantitative results provide an estimate for the mean emission factor. Because of the large variability in the results of emission tests on conventional and alternative fuels, a statistical approach needs to be adopted. The uncertainty for each fuel needs to be estimated, and comparison with the reference fuel made on the basis of the statistical variability. The method of uncertainty analysis that was adopted is explained in Appendix 3.

Table 1.1
Summary of information sources used for the quantitative evaluation of each fuel

Chapter	Fuel	Upstream	Tailpipe
Diesel fuels			
1 – This is the reference fuel; thus there is no summary in Part 1	Low Sulfur Diesel (LSD)	Australian petroleum refinery with hydro-desulfurisation unit	Diesel NEPM
2	Ultra Low Sulfur Diesel (ULSD)	Australian petroleum refinery with hydro-desulfurisation unit	Diesel NEPM Supplementary Study
3	Fisher-Tropsch Diesel (FTD)	Wang and Huang (1999)	Norton et al. (1998)
Biodiesel fuels			
4	Biodiesel (BD100)	Sheehan et al. (1998) and Ceuterick and Spirinckx (1999)	Sharp (1998) Tier 1 testing
5	Canola	Australian agricultural data	No data available due to the unsuitability of the fuel
Ethanol fuels			
6	Hydrated Ethanol	Kadam et al. (1999)	Skaraborg ethanol buses (CADETT, 1998)
7	Diesohol (E15D)	APACE data	Swedish data provided by APACE
Gaseous fuels			
8	Compressed Natural Gas (CNG)	Wang and Huang (1999)	Data from Andrew provided by ANGVC
9	Liquefied Natural Gas (LNG)	Wang and Huang (1999)	Data from Andrew provided by ANGVC
10	Autogas (LPG)	Standard refinery and natural gas operations	Nylund and Lawson (2000)
11	HD-5 Propane (LPG HD5)	Standard refinery and natural gas operations	Millbrook trials London bus data
Light vehicle fuels			
12 – Reference fuel	Premium Unleaded Petrol (PULP)	Standard refinery	MacLean (1998, 2000)
13	Anhydrous Ethanol	As for hydrated ethanol	MacLean (1998, 2000)
14	Petrohol (E10P)	Combines PULP and anhydrous ethanol	MacLean (1998, 2000)
Other fuels			
15	Hydrogen	Spath and Mann (2001)	Assumed no emissions

1.4 Sources of Quantitative Information

The quantitative calculations in the report are based on a variety of sources, summarised in Table 1.1. These sources were used, in conjunction with the extensive data set held by RMIT Centre for Design. This data set consists of emissions and energy use involved in Australian manufacturing. The upstream sources in Table 1.1 were used to provide default values when no Australian data was known, and the assumptions were examined during focussed roundtable discussions held with stakeholders, who examined the biodiesel, gaseous, and other fuels. Details of stakeholder interactions are given in Appendix 4.

1.5 Emissions from Diesel Engines

There are some generalisations concerning the emissions from diesel vehicles resulting from different fuels. These include:

- the less volatile and more aromatic the fuel, the higher the exhaust particle emissions;
- oxygenated fuels produce fewer particles due to more complete combustion, providing that other fuel-related qualities, e.g. cetane number, remain constant; and
- significant evaporative emissions may result from use of volatile fuels such as LPG or ethanol.

The presence of impurities such as sulfur will result in extra particle formation (in the form of sulfate). In regard to fuel consumption, provided the fuel is within the normal specification range, then for a given engine technology and transport task, fuel economy will be related to the energy content of the fuel.

However, it must be borne in mind that measurements of exhaust pollutants on chassis dynamometers show considerable variation between similar vehicles that can mask small changes that might result from using a different fuel. The reasons are that, for pollutants other than CO_2, we are dealing with trace amounts of unburnt fuel or combustion side reactions. These vary according to engine condition and maintenance and also, if non-steady state test cycles are used, the accuracy with which the cycles have been performed by the driver.

Table 1.2
Change (percent) in heavy-duty diesel vehicle emissions with variations in diesel fuel properties

Fuel property	CO_2	Particles	NO_x	NMHC	CO
Density 855 to 828 g/L	+0.07	-1.59	-3.57	+14.25	+5.0
Polyaromatics 8 to 1 percent	-0.60	-3.58	-1.66	-4.02	0.08(NS)
Cetane number 50 to 58	-0.41	0(NS)	-0.57	-6.25	-10.26
T95 370 to 325°C	+0.42	0(NS)	-1.75	+13.22	+6.54
Sulfur 2000 to 500 ppm	-	-13.0	-	-	-

Source: Faiz et al. (1996) - not applicable; (NS) not significant; positive values indicate an increase in emissions; negative values indicate a decrease in emissions.

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE) examined the effect of variations in European diesel fuel properties on emissions of light duty and heavy duty diesel engines. The heavy duty engines conformed to the Euro2 limits. The results are summarised in Faiz et al. (1996) and are reproduced in Table 1.2. They may also be found in Table 3.9 of Coffey (2000). Increasing cetane number and decreasing polycyclic aromatics are the two most significant variables in reducing heavy-duty diesel engine emissions. As Faiz et al. (1996) note, the absence of any effect on particulate matter (PM) emissions from changes in cetane number is different from the results of a number of US studies. This difference is most likely due to the higher cetane number of the EPEFE fuels (50 to 58) compared to the diesel fuels in the United States. Increasing cetane number from 50 to 58 seems to have little effect on PM emissions, but increasing it from 40 to higher levels such as 45 or 50 has a significant effect. Density and T95 are correlated as depicted in Table 1.2.

A subsequent program, the European automobile fuels programme (see http://europa.eu.int/comm/environment/autooil/), re-examined the Euro2 emissions data and extrapolated the results to estimate the performance of alternative fuels in Euro3 and Euro4 engines (Arcoumanis, 2000).

1.6 Greenhouse Gases and Other Emissions

In 1998, transport emitted about 22% of the national anthropogenic CO_2 emissions of 312.1 Mtonnes, but only 16% of total greenhouse gas emissions of 456 Mtonnes CO_2-equivalents (National Greenhouse Gas Inventory Committee, 2000). About 89% of these emissions come from road transport, including cars, trucks and buses. Table 1.3 gives a breakdown of the relative greenhouse gas emissions from transport and road transport.

Table 1.3
Australian greenhouse gas emissions from the transport sector and the road sub-sector in 1998

	CO_2 (Gg)	**CH_4 (Gg)**	**N_2O (Gg)**	**CO_2-equiv. (Gg)**
Transport	68433	23.18	11.91	72612
Road Transport	60753	20.48	11.69	64807

Source: National Greenhouse Gas Inventory Committee (2000)

In terms of the types of fuel used, current annual consumption is about 18,000 ML of automotive gasoline and about 12,500 ML of automotive diesel, with aviation using around 5,000 ML of turbine fuel. LPG and aviation gasoline consumption is relatively low. Strong growth is anticipated for aviation and road freight. Rail currently accounts for about 56% of non-urban freight (in net tonne-kms).

The greenhouse gases considered in this review are carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons. This particular group of greenhouse gases is sometimes called the Kyoto Protocol group of greenhouse gases, because they comprise the list of greenhouse gases specified in that protocol. The transport sector generates both ‘direct’ and ‘indirect’ greenhouse gases. Direct gases are radiatively active. Those emitted by transport include carbon dioxide, methane, nitrous oxide, and CFCs. The indirect greenhouse gases include carbon monoxide, other oxides of nitrogen and non-methanic volatile organic carbons. These do not have a strong radiative effect in themselves, but influence atmospheric concentrations of the direct greenhouse gases by, for example, oxidising to form CO_2 or contributing to the formation of ozone, a potent direct greenhouse gas. Present international agreement is to ignore such gases in the calculation of CO_2-equivalent greenhouse gases.

The concept of a global warming potential (GWP) has been used to enable different greenhouse gases to be compared with each other and expressed in CO_2-equivalents. The GWP factors reflect the different extent to which gases absorb infrared radiation and the differences in the time scales on which the gases are removed from the atmosphere. The GWP is used in the National Communications required by the UN Framework Convention on Climate Change. The Kyoto Protocol has adopted GWPs (with 100-year time horizon) as the basis for defining equivalences between emissions of different greenhouse gases during the 2008-2012 commitment period. These GWPs are given in Table 1.4.

The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide. Carbon dioxide that is generated as a result of the combustion of a renewable fuel (such as canola oil) is not to be included in greenhouse gas inventories.

Table 1.4
100-year greenhouse gas warming potentials

Gas	GWP
Carbon dioxide	1
Methane	21
Nitrous Oxide	310
Sulfur Hexafluoride	23900
CFC-11	3800*
CF_4	6500
C_2F_6	9200

*Direct only. Other estimates include indirect effects

With vegetable oils and ethanol derived from biomass, carbon dioxide emitted during combustion of the fuel is offset by that absorbed by the plant from the atmosphere during growth. However, greenhouse debits arise on the path from crop to canola or ethanol consumption in vehicles. The use of agricultural chemicals, fuelling of farm machinery, transport of the crop, processing of the crop, drying of liquid wastes and transport of canola or ethanol may all involve the use of fossil fuels and hence emissions of CO_2. Denitrification of fertilisers applied to the crop is also a major problem because N_2O, which has a high GWP, will be emitted.

These greenhouse debits are site specific because they depend on the crop grown, the source of fuel used to process the crop, and any additional release of greenhouse gases from the soil above natural levels.

1.6.1 Air Pollutants

The air pollutants to be considered are carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic hydrocarbons (NMHC), and particles with diameter less than 10 μm (PM10). These air pollutants are generated by transport vehicles, depending on the nature and composition of the fuel that is used, the type and age of the vehicle, the nature of the drive cycle, and the degree to which the vehicle is properly tuned.

Elevated concentrations of sulfur dioxide are not an issue in urban Australia (Manins et al., 2001). The only population centres to exceed the one hour standard of the ambient air quality NEPM are Mount Isa and Kalgoorlie, and in those locations the exceedances are caused by industrial emissions, not transport emissions. Accordingly, this report does not quantify sulfur dioxide emissions, but notes where they may be an issue.

NMHC exhaust emissions from conventional vehicles consist primarily of simple hydrocarbons (excluding methane). NMHC emissions from alcohol-based vehicles contain a greater proportion of very reactive and toxic compounds called aldehydes. Particles, smoke and NMHCs are composed of a mixture of many different compounds. Some of these compounds are toxic. Examples are benzene, formaldehyde, lead, chromium and benzo-a-pyrenes. In addition, alcohol blended fuels have potential evaporative emissions including unburnt alcohol.

There is a relatively small number of studies on air toxics in Australia. A greater difficulty is that there is no agreed Australian methodology for evaluating health risks associated with air toxics. This study reviews work on air toxics emissions from the fuels where such work exists, but generally had to use total hydrocarbon emissions as indicative of likely air toxics and their impact.

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2. Ultra Low Sulfur Diesel Summary

2.1 *Background*

Ultra low sulfur diesel (ULSD) is diesel fuel that meets either the Euro4 fuel specifications for diesel fuel, or the fuel specifications proposed by the Commonwealth for implementation in 2006. To date, the only Euro4 fuel specification that has been established is for sulfur. Directive 98/70/EC of the European Communities in 1998 set the maximum sulfur level from 2005 as being 50 ppm. Euro3 specifications for other parameters such as the cetane number, cetane index, density, T95, and PAH levels, apply until replaced by revised specifications. These limits are shown in Table 2.1.

Table 2.1
Ultra low sulfur diesel fuel quality specifications (Environment Australia, 2000a, 2000b)

Fuel parameter	**Euro 3 (applicable from 2000)**	**Euro 4 (applicable from 2005)**	**Commonwealth (1 January 2006)**
Sulfur (ppm)	350 (max)	50	50 (max)
Cetane number	51 (min)	-	-
Cetane index	46 (min)	-	50 (min)
Density at 15^{o}C (kg/m^3)	845 (max)	-	820 to 850
Distillation T95 (^{o}C)	350 (max)	-	360 (max)
PAH (% by mass)	11 (max)	-	11 (max)

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. Low sulfur diesel is produced in refineries with a hydrodesulfurisation unit. ULSD requires either a hydrocracker, or the use of higher pressures in the hydrodesulfurisation unit (hydrofining). As at March 2001 Western Australia and Queensland had passed legislation mandating a diesel sulfur content of 500 ppm or less.

2.2 *Results*

Two modes of ULSD manufacture are examined. The first assumes that 50% of Australian ULSD production comes from hydrocracking, and the other 50% from hydrofining. The second (marked as 100% reprocessing) assumes that all ULSD comes from hydrofining.

2.2.1 Greenhouse gas emissions

Figure 2.1 depicts the greenhouse gas emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

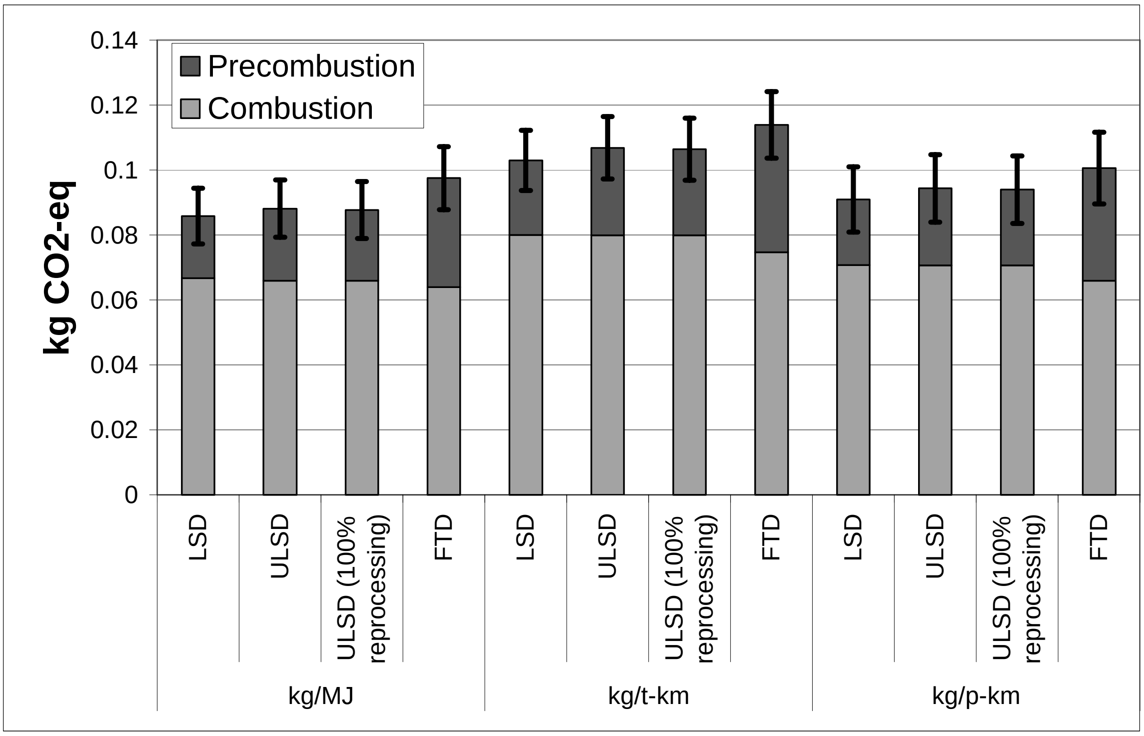

Figure 2.1
Exbodied emissions of greenhouse gases for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance

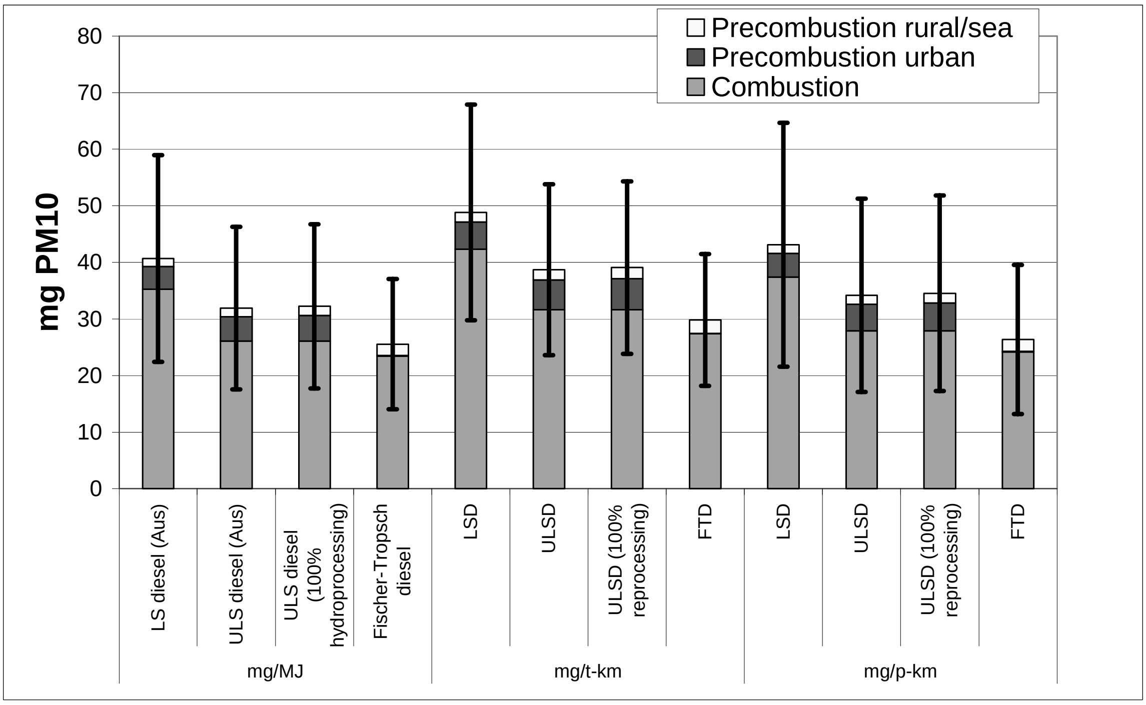

Figure 2.2
Exbodied emissions of particulate matter for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance

2.2.2 *Particulate matter emissions*

Figure 2.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

2.2.3 *Emissions of oxides of nitrogen*

Figure 2.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

2.2.4 *Hydrocarbons*

Figure 2.3 depicts the oxides of non-methanic hydrocarbon (HC) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger basis for buses using the same energy intensities previously noted.

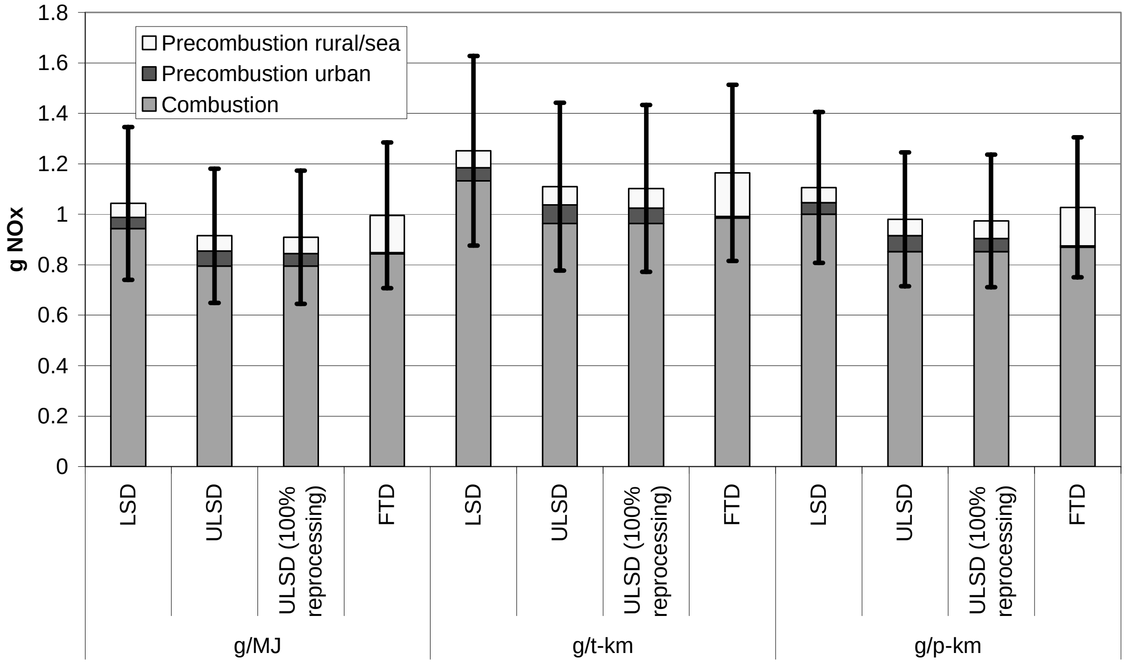

Figure 2.3
Exbodied emissions of oxides of nitrogen for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance

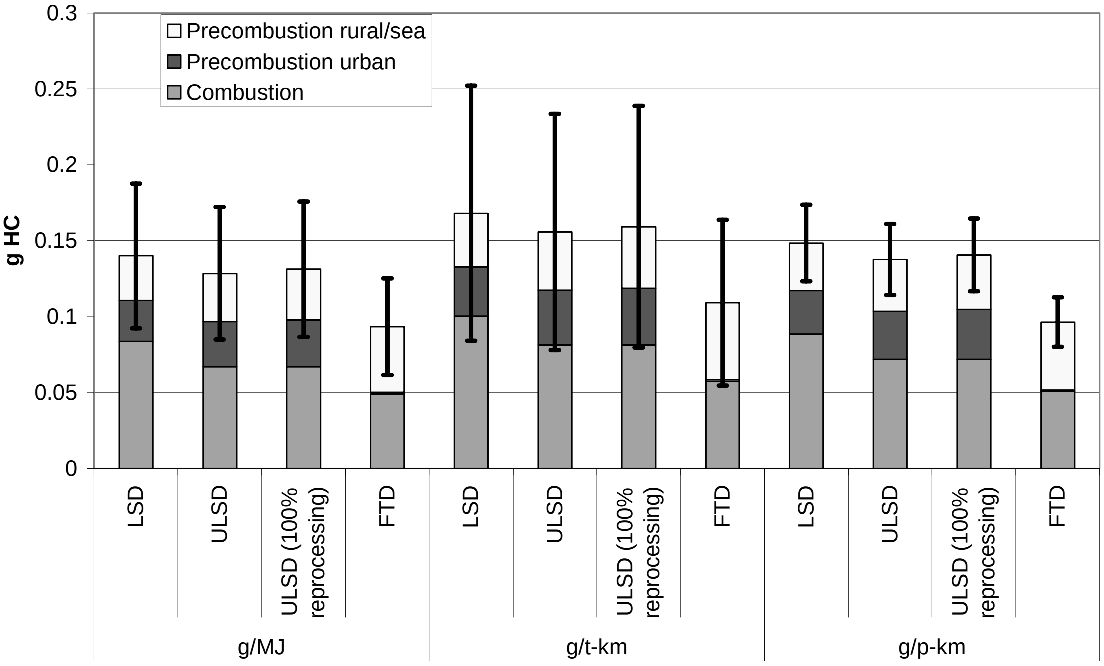

Figure 2.4
Exbodied emissions of hydrocarbons for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance

2.3 Viability and Functionality

There is a need to match the fuel with the appropriate vehicle technology. The major benefits of the move to ULSD are provided by the ability to use advanced technology in the engine and the catalyst. These components are often sensitive to sulfur. We expect vehicle emissions to be lower than those presented in the results section when ULSD is used with the appropriate Euro4 fuelled engines. Using ULSD in a Euro2 vehicle provides only marginal improvement in tailpipe emissions over low sulfur diesel. However, the emissions from a Euro4 vehicle with advanced on-board diagnostics and a particulate trap will be dramatically better.

2.4 Health Effects

Epidemiological evidence indicates that decreasing particle emissions reduces morbidity and reduces hospital admissions as a result of respiratory illness. At present, diesel engines are a major source of fine particles – diesel exhaust releases particles at a rate about 20 times greater than that from petrol-fuelled vehicles. Thus the combination of ULSD and particulate traps on vehicles using ULSD will have the beneficial effect of reducing the emissions of particles. ULSD upstream particulate and HC emissions are similar to LSD. ULSD tailpipe HC emissions are similar to LSD and have little effect on emissions of VOCs and aldehydes. ULSD reduces particulate emissions compared to LSD.

OH&S issues associated with ULSD are the same as those associated with LSD (the reference fuel).

2.5 Environmental Issues

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ULSD. The combination of ULSD and oxygenating catalysts or “de-NOx” catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality. The upstream environmental issues associated with ULSD are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

ESD issues

The modern western economy is based on petroleum products, of which diesel is one. The current concern over climate change highlights the burning of fossil fuels as one of the main causes. Examined from the ESD perspective of equity, efficiency and ecological integrity, even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity. Climate change, and global warming in particular, pose threats to inter-generational equity.

Sustainability

Crude oil supplies are sustainable in the medium term (to at least 2020), though Australian imports will need to rise as the Victorian oil fields start to decline in production. The key sustainability issues for diesel fuel depend on global oil supply.

Groundwater contamination

Diesel is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from diesel itself can also occur, especially from leaks at service stations and refuelling depots that have been known to contaminate groundwater supplies.

2.6 ADR Compliance

Ultra low sulfur fuel is being introduced specifically to enable the introduction of technology to meet Euro4 fuel specifications. The ADR have been based on this fuel so that, by definition, there should be no potential to compromise vehicles’ compliance with gazetted ADR standards.

2.7 Summary

The advantages of ultra-low sulfur diesel are:

- ULSD contains little sulfur and few aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The low sulfur content means that oxidation catalysts will be more efficient.
- The existing diesel infrastructure can be used, unchanged, for ultra-low sulfur diesel.
- Low-sulfur diesel can be used in existing diesel engines.
- Diesel is one of the safest of the automotive fuels.

The disadvantages of ultra-low sulfur diesel are:

- Diesel exhaust (including ULSD exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, ULSD produces more exbodied greenhouse gases than LSD.

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3. Fischer-Tropsch Diesel

3.1 Introduction

Fischer-Tropsch diesel (FTD) is a synthetic fuel produced from the conversion of natural gas into a diesel fuel. The fuel thus formed is superior to crude-oil based diesel in certain ways, principally the high cetane number and the zero sulfur content. It is also known as GTL diesel, where the acronym refers to “gas to liquid” conversion. Gas to liquid fuels conversion is of relevance to Australia, because of the large natural gas deposits in the north-west shelf.

This study is required to use Australian data where available. At the time of writing SASOL-Chevron was not in a position to submit emissions data that would be applicable to its production of FTD and the use of FTD in Australia. It is recommended that a separate study be undertaken when that data becomes available

3.2 Results

3.2.1 Greenhouse gas emissions

Figure 3.1 depicts the greenhouse gas emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

The extra processing required to make synthetic diesel means that the exbodied emissions of greenhouse gases are greater from FTD than from LSD, even though there are lower tailpipe emissions.

3.2.2 Particulate matter emissions

Figure 3.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of FTD are markedly lower than those of LSD.

3.2.3 Emissions of oxides of nitrogen

Figure 3.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

The upstream processing required to produce FTD means that its NOx emissions are greater than those of LSD, even though the tailpipe emissions are lower.

3.2.4 Emissions of hydrocarbons

Figure 3.4 depicts the emissions of non-methanic hydrocarbon (HC) estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

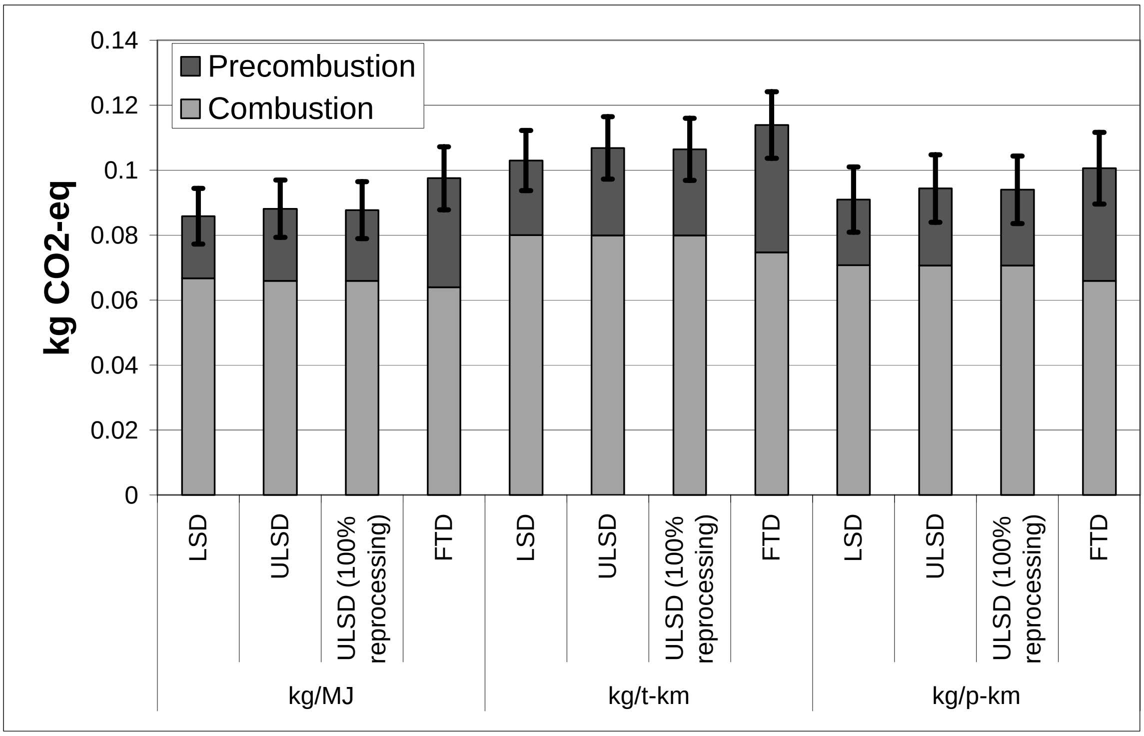

Figure 3.1
Exbodied emissions of greenhouse gases for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.

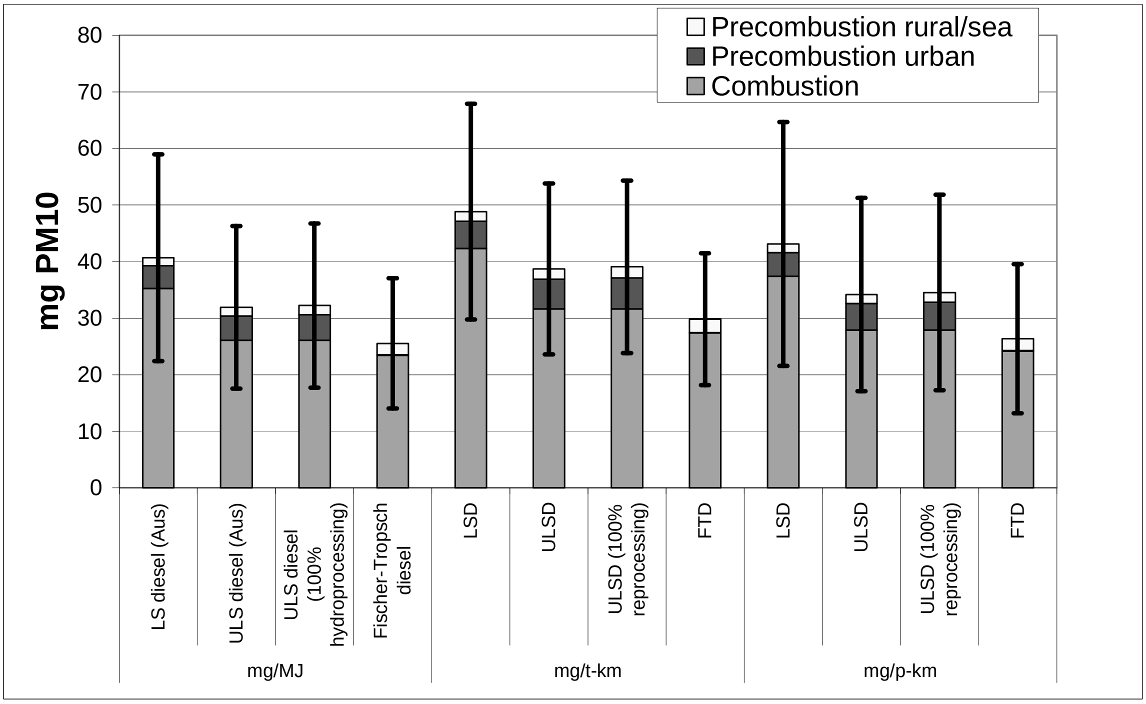

Figure 3.2
Exbodied emissions of particulate matter for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.

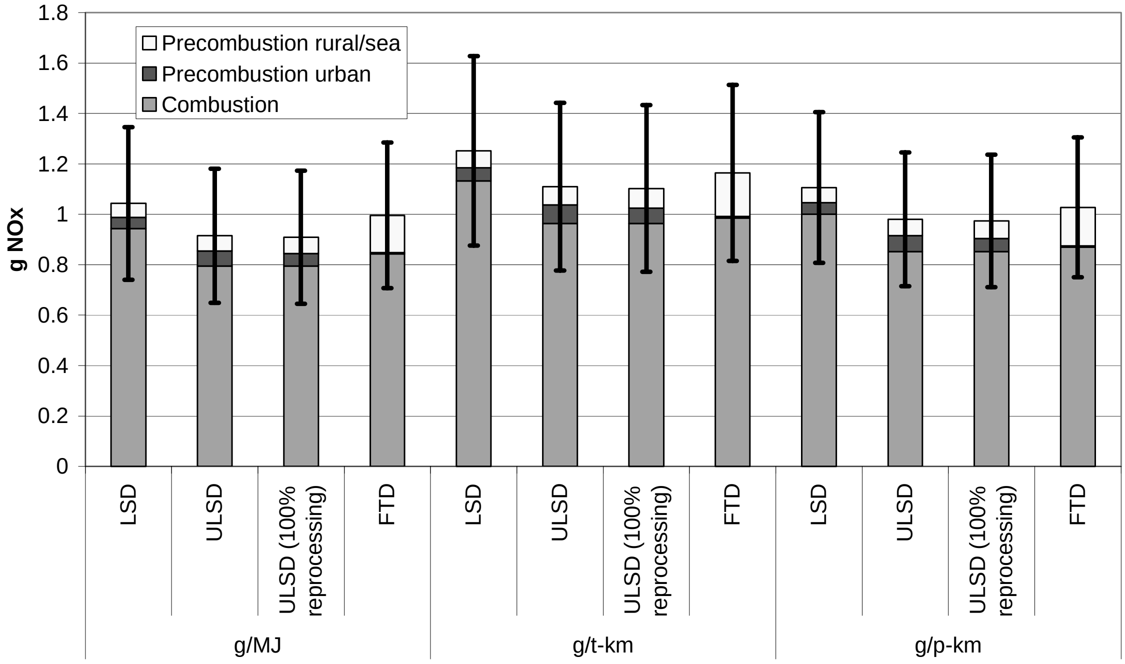

Figure 3.3
Exbodied emissions of oxides of nitrogen for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.

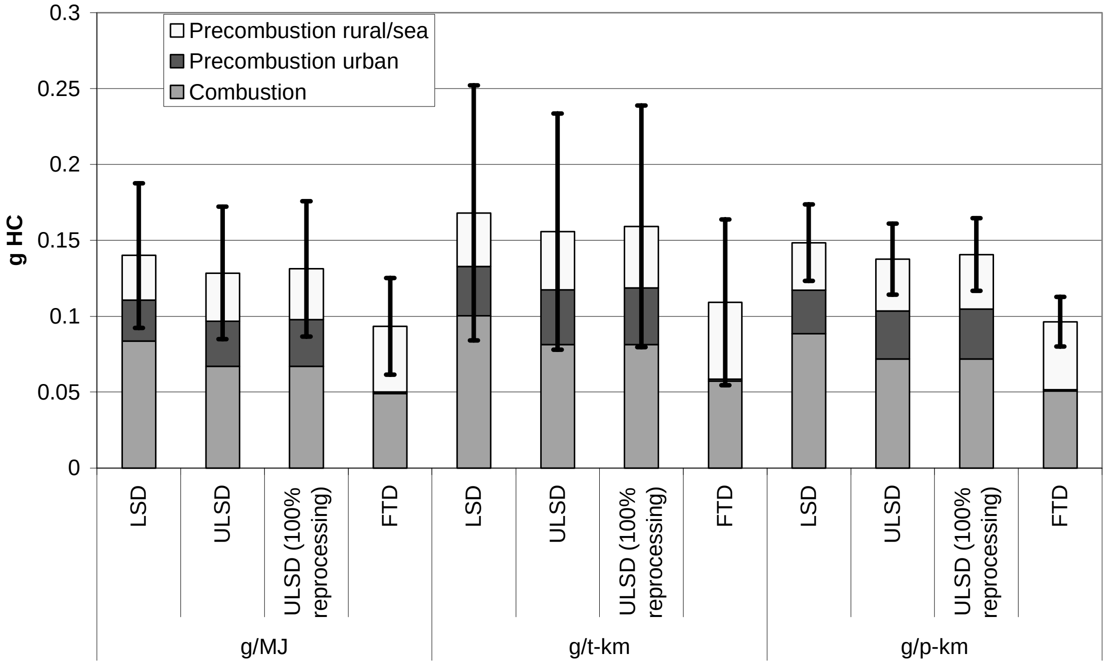

Figure 3.4
Exbodied emissions of hydrocarbons for diesel fuels, low sulfur diesel (LSD), ultra low sulfur diesel (ULSD) and Fischer-Tropsch diesel (FTD) per unit energy and per unit distance.

3.3 Viability and Functionality

FT diesel has the same viability and functionality as diesel fuel.

3.4 Health Issues

FT diesel is an extremely low sulfur diesel, with sulfur content less than 10ppm. The health benefits, when compared to the low sulfur diesel reference fuel will be at least those of ultra low sulfur diesel (ULS). There are claims that there are 20% reductions in aromatics from the tailpipes of vehicles using such extremely low sulfur diesel fuels.

FT diesel upstream emissions of both particulates and HC are substantially less than for LSD. FT diesel tailpipe emissions of both particulates and HC are marginally less than for LSD.

3.5 Environmental Impact and Benefits

Greene (1999) comprehensively reviews the environmental issues involved with GTL fuels. The environmental impacts are the same as those for diesel fuel, with the benefit of lower air pollutant emissions and increased resource security through a lowered dependence on imported oil. An FTD plant does not produce undesirable co-products, unlike a refinery, which produces heavy fuel oil and coke.

ESD issues

Gas to liquids conversion is based on the use of natural gas, which is a fossil fuel. The current concern over climate change highlights the burning of fossil fuels as one of the main causes. Examined from the ESD perspective of equity, efficiency and ecological integrity, even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity. Climate change and global warming pose threats to inter-generational equity.

Sustainability

FTD is made from natural gas. Australian known reserves of natural gas are estimated to last for the next 90 years, ensuring a sustainable, indigenous supply of natural gas as the feedstock for the FTD.

Groundwater contamination

FT diesel does not require the transport of crude oil. Environmental damage from any liquid hydrocarbon can occur, especially from leaks at refuelling depots that may contaminate groundwater supplies.

3.6 ADR Compliance

Ultra low sulfur fuel is being introduced specifically to enable Euro4 fuel specifications to be met. The ADR have been based on this fuel. There should thus be no potential for an even lower sulfur fuel such as FT diesel to compromise vehicles' compliance with gazetted ADR standards.

3.7 Summary

The advantages of FT diesel are:

- FT diesel contains virtually no sulfur or aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The absence of sulfur means that oxidation catalysts and particulate traps will operate at maximum efficiency.
- The existing diesel infrastructure can be used, unchanged, for Fischer-Tropsch Diesel.
- FT diesel can be used in existing diesel engines.

- Diesel is one of the safest of the automotive fuels.
- An FT plant does not produce any of the less desirable co-products from a refinery, such as heavy fuel oil or coke.
- Provided an FT plant uses an oxygen feed, it produces a pure CO_2 stream that provides an option for the collection and sequestration of CO_2.

The disadvantages of FT diesel are:

- Diesel exhaust (including FT diesel exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, FT diesel produces more exbodied greenhouse gases than any of the conventional or alternative fuels studied in this report.

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4. Biodiesel

4.1 Introduction

Biodiesel is a generic name for fuels obtained by esterification of a vegetable oil. The esterification can be done either by methanol or by ethanol. Biodiesel can be used in a diesel engine without modification. By the year 2002 it is expected that there will be a European wide standard for biodiesel.

Canola is a member of the *Brassica* Family, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed, with less crucic acid and glucosinolates than rapeseed. Grown for its seed, the seed is crushed for the oil contained within. After the oil is extracted, the by-product is a protein rich meal used by the intensive livestock industry.

Soybeans are a bushy, leguminous plant, *Glycine max*, native of South-East Asia that is grown for the beans, which are used widely in the food industry, for protein in cattle feed and for oil production.

Soybeans are grown predominantly in the wheat belts of Queensland and NSW and to a lesser extent in Victoria.

Tallow comes from meat rendering. This evaporates the moisture and enables the fat, known as ’tallow’, to be separated from the high-protein solids, known as ’greaves’. Pure tallow is a creamy-white substance. The greaves are pressed, centrifuged or subjected to a process of solvent extraction to remove more tallow, before being ground into meat and bone meal (MBM).

Current possibilities for the processing of waste cooking oils appear to be:

- Treatment and use in stockfeed in Australia
- Export to Asia for soap or stockfeed production
- Use for production of biodiesel

It is also clear that some waste cooking oil is not collected and is disposed of in landfill or other locations. Biodiesel made from waste cooking oil has come to be known as McDiesel, because the largest source of waste cooking oil is McDonald’s restaurants.

4.2 Full Fuel-Cycle Analysis of Emissions

Results are given for biodiesel made from three types of seed crops (canola, soybean, and rape), for biodiesel made from tallow and for biodiesel from waste cooking oil. In the case of these last two feedstocks, it has been assumed that tallow is a commercial product, whereas the cooking oil is a waste product. In both cases an alternative allocation (alt. allocat.) has been made that allows for the opposite situation.

4.2.1 Greenhouse gas emissions

Figure 4.1 depicts the greenhouse gas emissions estimated for biodiesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

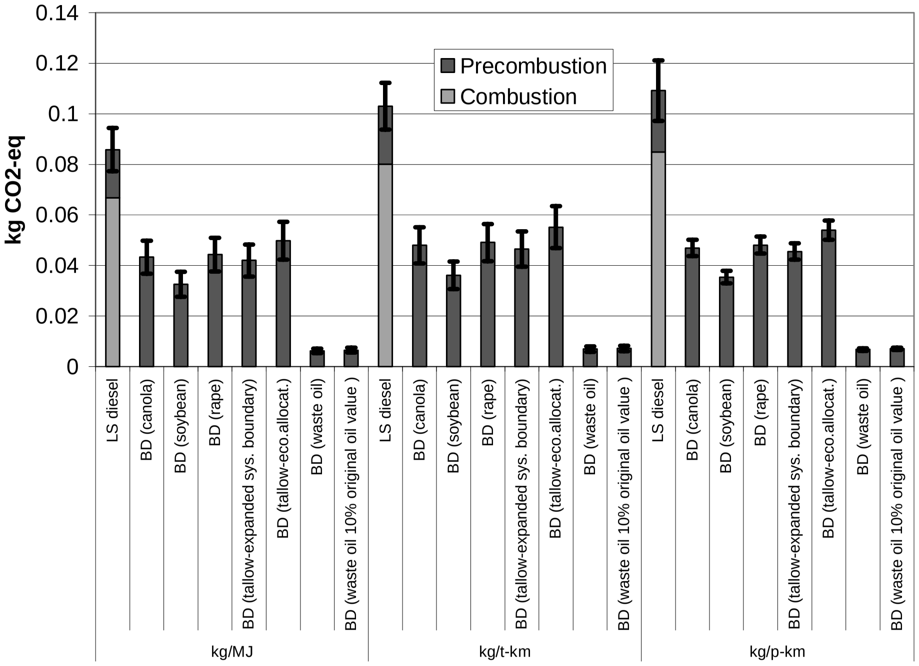

Figure 4.1
Exbodied emissions of greenhouse gases for biodiesel fuels and low sulfur diesel (LSD, the reference fuel). Tallow and cooking oil are treated both as waste and as physical inputs.

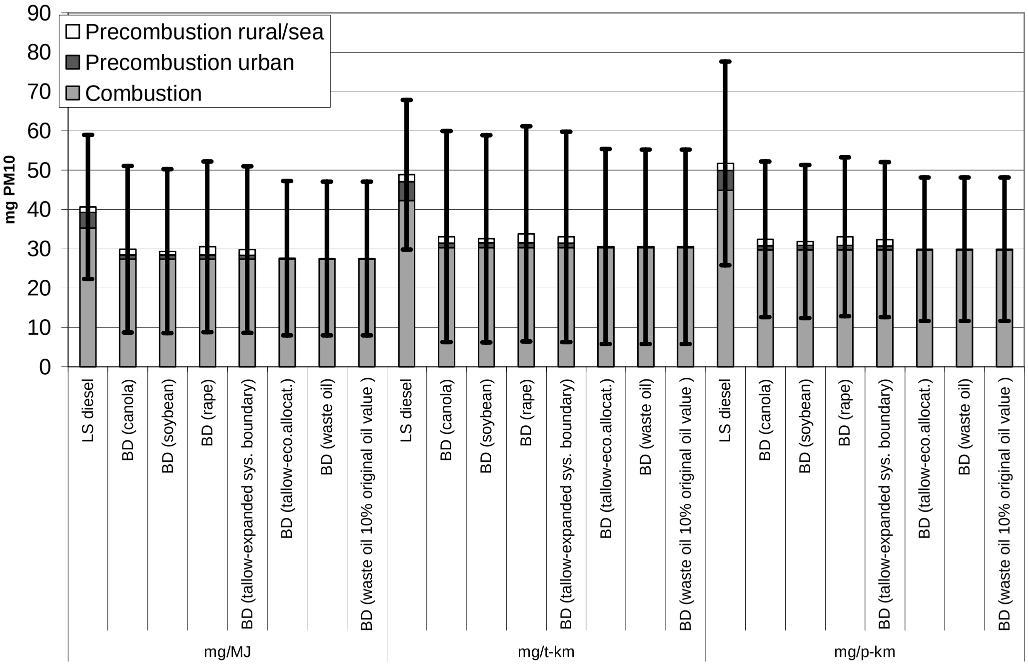

Figure 4.2
Exbodied emissions of particulate matter for biodiesel fuels and low sulfur diesel (LSD, the reference fuel). Tallow and cooking oil are treated both as waste and as physical inputs.

4.2.2 Particulate matter emissions

Figure 4.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

4.2.3 Emissions of oxides of nitrogen

Figure 4.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

4.2.4 Emissions of hydrocarbons

Figure 4.4 depicts the non-methanic hydrocarbon (HC) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

The variability in the results is very evident. On the basis of the data that we used for the analysis, soy biodiesel emits more hydrocarbons than the reference fuel as a result of tailpipe emissions – the upstream hydrocarbon emissions are less. Canola and rape are comparable to LSD, being higher on a per energy basis but lower on a per distance basis. Tallow and waste oil have surprisingly small hydrocarbon emissions.

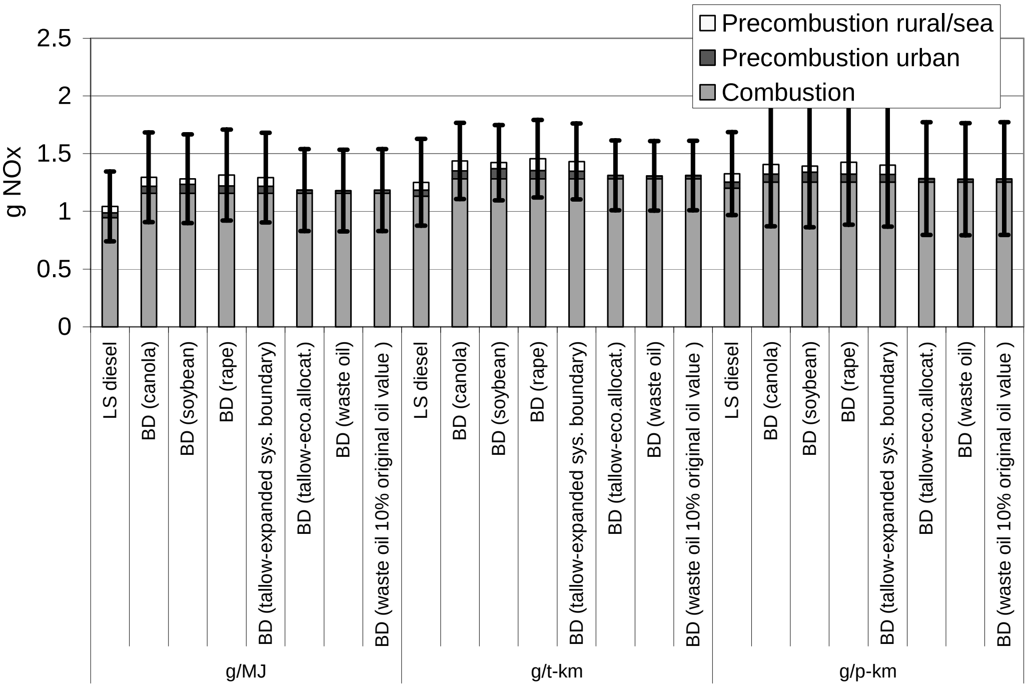

Figure 4.3
Exbodied emissions of oxides of nitrogen for biodiesel fuels and low sulfur diesel (LSD, the reference fuel). Tallow and cooking oil are treated both as waste and as physical inputs.

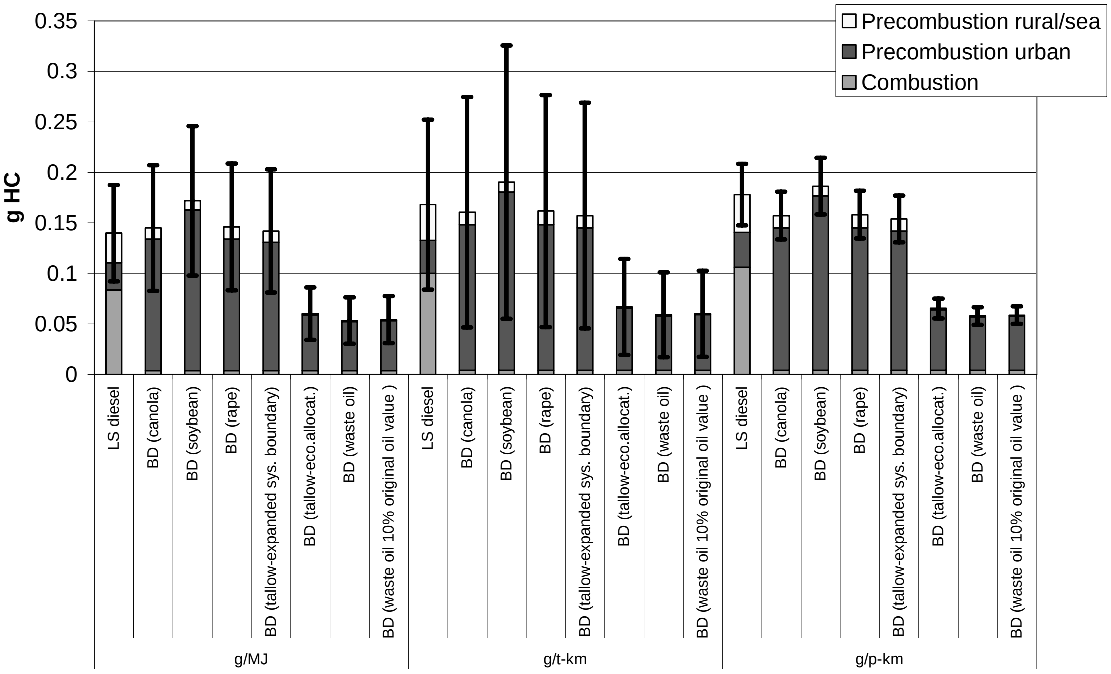

Figure 4.4
Exbodied emissions of hydrocarbons for biodiesel fuels and low sulfur diesel (LSD, the reference fuel). Tallow and cooking oil are treated both as waste and as physical inputs.

4.3 Viability, Functionality and Health Issues

There appear to be no health risks of air toxic emissions from biodiesel with respect to mortality, toxicity, fertility or teratology. All air toxic emissions from biodiesel are lower than equivalent diesel emissions except for acrolein. Though highly toxic, the slight increase in acrolein is offset by the decrease in the equally toxic aldehydes.

The National Biodiesel Board web site also points out that biodiesel over time will soften and degrade certain types of elastomers and natural rubber compounds. Precautions are needed when using high percent blends to ensure that the existing fueling system, primarily fuel hoses and fuel pump seals, do not contain elastomer compounds incompatible with biodiesel.

Cummins will warranty only biodiesel blends, though Caterpillar will warranty biodiesel in certain of their engines. In contrast to the cautious attitude of the manufacturers, the “truck in the park” project and other road-test projects found no difference in engine viability and functionality between diesel and biodiesel.

4.4 Environmental Issues

ESD issues

Biodiesel is made from agricultural crops and is thus more environmentally friendly and ecologically sustainable than fossil fuels. Our results confirm that, on a life-cycle basis, biodiesel is more climate-friendly than diesel. The carbon emissions caused by agricultural production and fertiliser production are less than the exbodied emissions from diesel made from fossil fuels.

Sustainability issues

Biodiesel is made from either crops or from animal product. Its feedstock is thus a renewable resource. Biodiesel will be a niche fuel, albeit a very useful one, because there is not sufficient area to grow the plants needed to convert all of Australia's diesel fuel usage to biodiesel.

Groundwater contamination

Not an issue with biodiesel, except for the possible use of i) pesticides or fertiliser during the growth of the crop from which the biodiesel is made, and ii) runoff from cattle feedlots (for biodiesel made from tallow).

4.5 ADR Compliance

100% biodiesel can be expected to meet all future Australian Design Rules for all pollutants except oxides of nitrogen which may be slightly above Euro3 and Euro4 standards, and possibly the particulate matter standard for Euro3. Arcoumanis notes that there is limited data for 100% biodiesel on which to make this judgement. He also indicates that a blend of 20% - 30% biodiesel with diesel in heavy vehicles is expected to meet all Euro 4 standards.

4.6 Summary

The advantages of biodiesel are:

- It is a renewable bio-based fuel and, as such, has lower life cycle CO_2 emissions than diesel derived from mineral oils.
- Neat biodiesel contains almost no sulfur and no aromatics. In a properly tuned engine this is expected to lead to lower particulate exhaust emissions.
- The material is bio-degradable and non-toxic.
- As an oxygenated compound, it reduces the non-soluble fraction of the particles.
- The PAH content of exhaust particles is reduced.
- In a mixture with low-sulfur diesel, biodiesel can act as a lubricity improver (Arcoumanis, 2000).
- The absence of sulfur allows more efficient use of oxidation catalysts.

The disadvantages of biodiesel are:

- Constraints on the availability of agricultural feedstock impose limits on the possible contribution of biodiesels to transport.
- The kinematic viscosity is higher than diesel fuel. This affects fuel atomisation during injection and requires modified fuel injection systems.
- Due to the high oxygen content, it produces relatively high NOx levels during combustion.
- Oxidation stability is lower than that of diesel so that under extended storage conditions it is possible to produce oxidation products that may be harmful to the vehicle components.
- Biodiesel is hygroscopic. Contact with humid air must be avoided.
- Production of biodiesel is not sufficiently standardised. Biodiesel that is outside European or US standards can cause corrosion, fuel system blockage, seal failures, filter clogging and deposits at injection pumps.
- The lower volumetric energy density of biodiesel means that more fuel needs to be transported for the same distance travelled.
- It can cause dilution of engine lubricant oil, requiring more frequent oil change than in standard diesel-fuelled engines.
- A modified refuelling infrastructure is needed to handle biodiesels, which adds to their total cost.

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5. Canola

5.1 Background

Canola is a member of the *Brassica* Family, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed. Grown for its seed, the seed is crushed for the oil contained within. After the oil is extracted, the by-product is a protein-rich meal used by the intensive livestock industry.

5.2 Results

At present canola oil, per se, is not an automotive fuel, thus no results are presented because no results are available.

5.3 Viability and Functionality

The power output and tailpipe emissions using plant or animal oils are in most cases comparable with the power output and the emissions when running on petroleum diesel fuel, the main problem encountered has been the higher viscosity of the oils causing difficult starting in cold conditions, the gumming up of injectors, the coking-up of valves and exhaust, and the often high melting or solidification point of many vegetable and animal fats and oils. High melting points or solidification ranges can cause problems in fuel systems such as partial or complete blockage as the oil thickens and finally solidifies when the ambient temperature falls. The engine can quickly become gummed-up with the polymerised oil. With some oils, engine failure can occur in as little as 20 hours.

Only coconut oil has an iodine value low enough to be used without any special precautions in a unmodified diesel engine. However with a melting point of 25°C, the use of coconut oil in cooler areas would obviously lead to problems.

All of these problems can be at least partially alleviated by dissolving the oil or hydrogenated oil in petroleum diesel. Linseed oil for example, could be mixed with petroleum diesel at a ratio of up to 1:8. Likewise coconut oil can be thinned with diesel or kerosene to render it less viscous in cooler climates. Another method is to emulsify the oil or fat with ethanol.

5.4 Health Issues

The health issues associated with the use of canola oil in a diesel engine are not known.

5.5 Environmental Impact and Benefits

The environmental issues associated with the use of canola oil in a diesel engine are not known. If diesel vehicles were modified to run on straight vegetable oils then the following environmental considerations would apply.

ESD issues

Canola is made from agricultural crops and is thus widely perceived to be more environmentally friendly than fossil fuels.

Sustainability issues

Sustainability is not currently an issue for canola as a transport fuel because there is no demand for it.. Australia has a production land base able to increase canola, though low oilseed prices could restrict expansion.

Groundwater contamination

Not an issue with vegetable crops, except for the possible use of pesticides or fertiliser during their growth.

6. Hydrated Ethanol

6.1 Background

Ethanol (C_2H_5OH) is an alcohol, an oxygenated organic carbon compound. It is the intoxicating component of alcoholic beverages, and is also used as a solvent (methylated spirits). By contrast, diesel is a mixture of a range of hydrocarbon compounds, none of which contains oxygen. In blended fuels, the addition to diesel of the oxygen contained in the alcohol changes a number of important fuel characteristics. These include changes in combustion properties, energy content and vaporisation potential.

Ethanol will easily blend with gasoline but not with diesel. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations. This chapter will examine hydrated ethanol produced from wheat, sugar cane, molasses and wood, and will discuss one source of ethanol from a non-renewable resource. Hydrated ethanol production is a one-stage refining process, unlike the two-stage anhydrous ethanol. However, from the viewpoint of the LCA, the upstream emissions for ethanol production will be different for every process.

Ethanol can be manufactured from:

- biomass via the fermentation of sugar derived from grain starches or sugar crops;
- biomass via the utilisation of the non-sugar lignocellulosic fractions of crops;
- petroleum and natural gas via an ethylene (C_2H_4) intermediate step (reduction or steam cracking of ethane [C_2H_6] or propane [C_3H_8] fractions).

6.2 Results

We present results for seven different scenarios. These are ethanol made from wheat using natural gas as the energy source, ethanol made from wheat using wheat straw as the energy source (wheat WS), ethanol made from wheat starch, ethanol from molasses treated as a waste product, ethanol from molasses treated on the basis of physical inputs (alt. allocation), ethanol from lignocellulosic processes (woodwaste), and ethanol via ethylene.

6.2.1 Greenhouse gas emissions

Figure 6.1 depicts the greenhouse gas emissions estimated for ethanol and diesohol. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basisfor buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

As may be expected, the use of a renewable fuel, such as ethanol considerably reduces greenhouse gas emissions because the greenhouse gas accounting rules mean that there are no tailpipe emissions from the combustion of ethanol. If ethanol is made from a fossil fuel (as in the case of ethanol via ethylene) then there are more greenhouse gas emissions involved than if diesel was used.

6.2.2 Particulate matter emissions

Figure 6.2 depicts the particulate matter (PM10) emissions estimated for ethanol. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basisfor buses using the same energy intensities previously noted. In all cases but one the emissions of PM10 are less from ethanol than from the reference fuel (LSD). The exception is the case where the energy to manufacture the ethanol comes from the use of wheat straw (rather than from natural gas). Combustion of the wheat straw generates higher levels of PM10 than use of natural gas or bagasse.

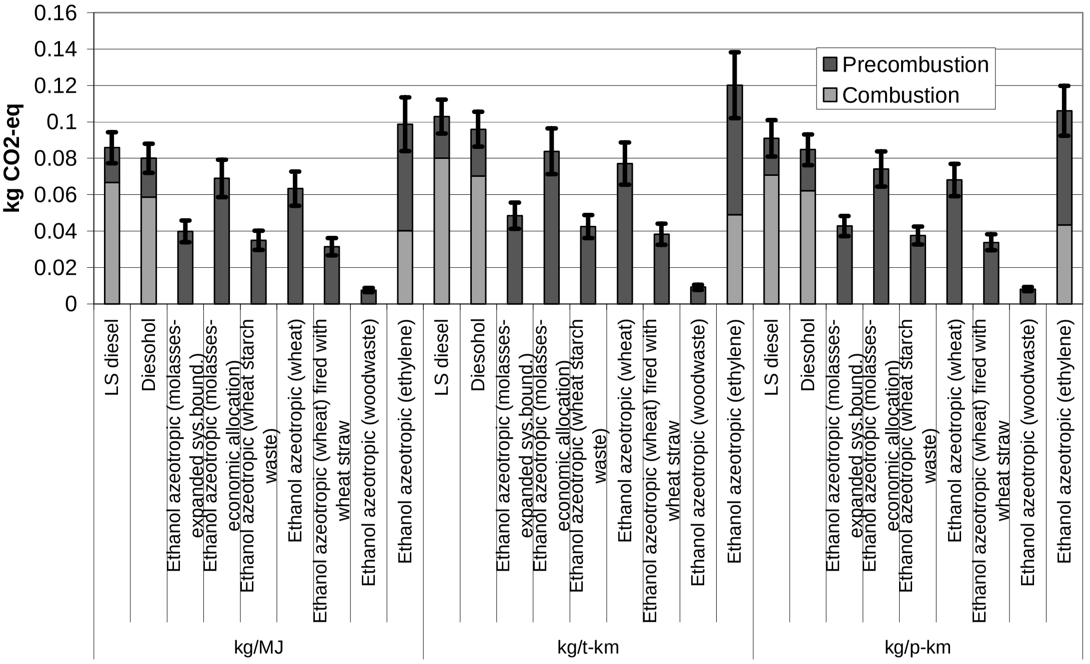

Figure 6.1
Exbodied emissions of greenhouse gases for diesohol and ethanol made from various sources.

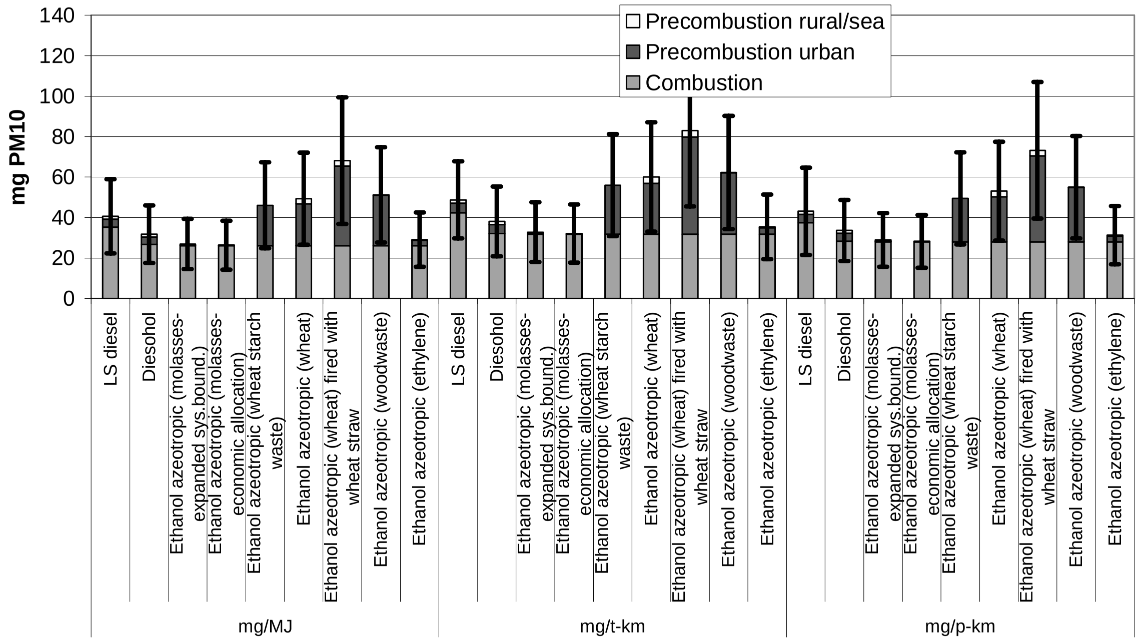

Figure 6.2
Exbodied emissions of particulate matter for diesohol and ethanol made from various sources.

6.2.3 Emissions of oxides of nitrogen

Figure 6.3 depicts the oxides of nitrogen (NOx) emissions estimated for alcohol fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basisfor buses using the same energy intensities previously noted. As a general rule the NOx emissions from ethanol, on a full fuel cycle basis, are comparable to those of the reference fuel.

6.2.4 Emissions of hydrocarbons

Figure 6.4 depicts the non-methanic hydrocarbon (HC) emissions estimated for alcohol fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basisfor buses using the same energy intensities previously noted.

Wheat straw and ethylene have very high precombustion emissions of hydrocarbons. Ethanol made from other sources has emissions comparable to those of the reference fuel.

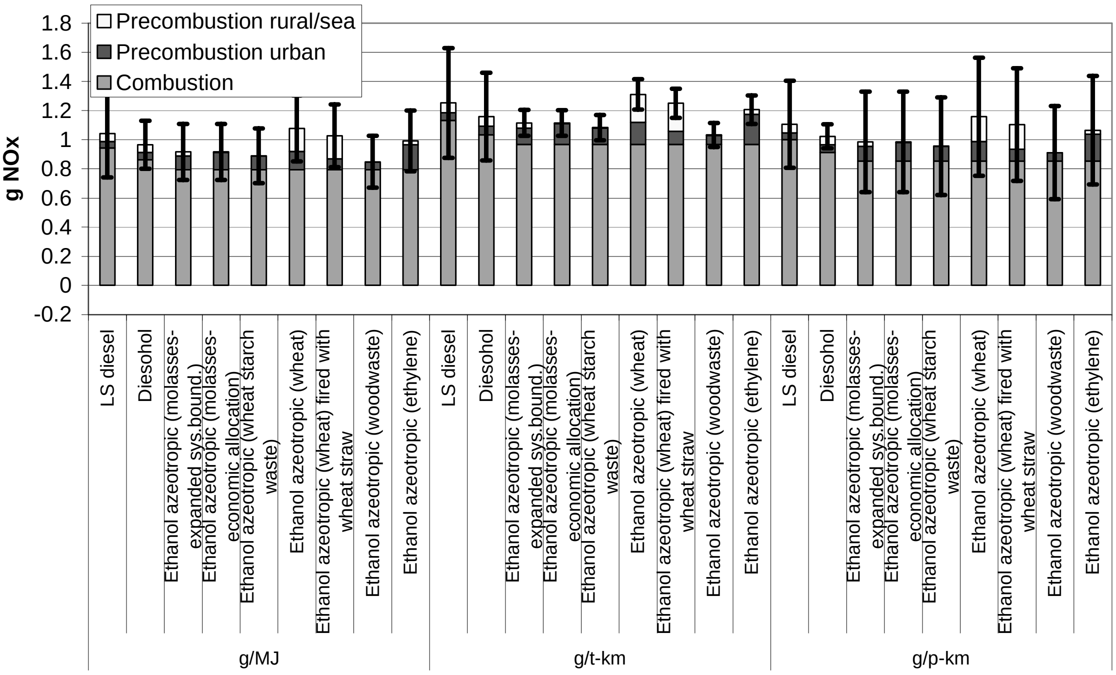

Figure 6.3
Exbodied emissions of oxides of nitrogen for diesohol and ethanol made from various sources.

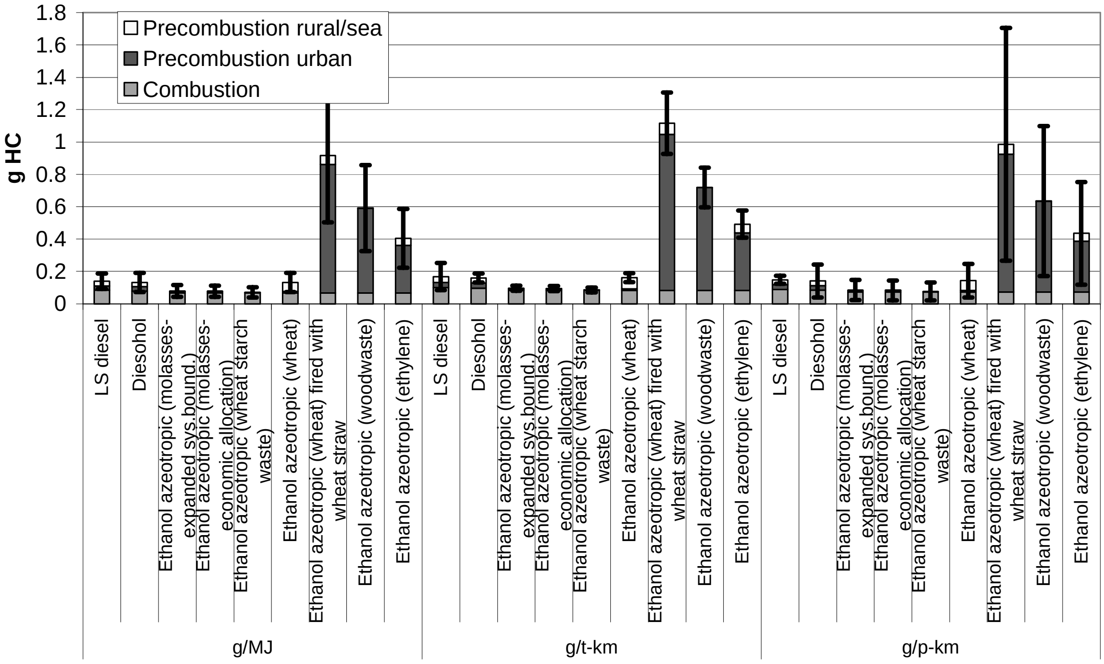

Figure 6.4
Exbodied emissions of hydrocarbons for diesohol and ethanol made from various sources.

6.3 *Viability and Functionality*

The third generation fleet of ethanol buses runs with oxidation catalysts. In general, ethanol buses have enlarged holes for the fuel injector, modified injection timing, and increased fuel pump capacity. Gaskets and filters need to be alcohol-resistant. In addition, because ethanol has a tendency to dissolve the oil film on greased metal surfaces, castor oil needs to be used for fuel pump lubrication. US transit authorities experienced high rates of engine failure and poor engine reliability with the earlier generation of ethanol buses.

6.4 *Health and OH&S*

Ethanol upstream emissions of particulate matter and HC range from lower to higher than LSD emissions depending on the feedstock. Ethanol tailpipe emissions of particulate matter and HC for all feedstocks are marginally less than LSD. Limited tailpipe emissions data indicate that ethanol is likely to reduce benzene and 1,3 butadiene emissions compared with LSD, formaldehyde emissions would be similar, while acetaldehyde emissions would increase substantially.

Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and a moderate irritant.

The OHS issues in the lifecycle of ethanol are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with ethanol compared with LSD, no OHS issues unique to the production and distribution of ethanol have been identified.

Diesel fuel has very low vapour pressure, but the addition of alcohol to diesel (for example diesohol) creates a fuel with a vapour pressure similar to that of ethanol. While modern gasoline vehicles have some evaporative emission control measures, diesel vehicles do not. Evaporative emissions may be a significant problem from unmodified vehicles using ethanol based fuels, but this needs to be tested.

To contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure.

6.5 Environmental Issues

ESD issues

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid. Provided that the source of ethanol is not fossil fuels then it satisfies ESD principles.

In particular, we draw attention to the fact that appropriate disposal of the refinery waste-products is crucial to environmental impacts or benefits. Dunder application is often criticised as being the cause of poor waste quality in Queensland, though there is little evidence of this (www.sunfish.org.au/fishkills/fishkills.htm). Conversely, appropriate and careful disposal of dunder means that many farmers in the district near Sarina now use it as a fertiliser and soil condition - even though it was once considered a poison.

Sustainability

Ethanol from sugar or wheat is liable to be a niche fuel and thus there are no sustainability issues associated with it. Large-scale usage of ethanol will require ligno-cellulosic production to be economical.

Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia’s oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia’s croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large-scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

Groundwater

We are not aware of any issues related to groundwater contamination except to note that in the US the replacement of methyl tertiary butyl ether (MTBE) by ethanol in oxygenated fuels was specifically done to reduce groundwater contamination.

We also note ethanol when used as a heavy vehicle fuel may contain 2.3% MTBE. This additive was extensively examined in the US where 15% MTBE (or 7.5% ethanol) was added to petrol to achieve the 2.7% oxygen content required under the Clean Air Act. The use of MTBE is no longer permitted because of concerns in relation to health as a result of groundwater, and hence drinking water, contamination by MTBE.

6.6 Expected Future Emissions

Ethanol can be expected to meet all future Australian Design Rules for all pollutants except hydrocarbon which may be slightly above Euro3 and Euro4 standards.

6.7 Summary

6.7.1 Advantages

- As a renewable fuel, ethanol produces less fossil CO_2 than conventional fuels.
- Particulate emissions are lower with ethanol than with conventional fuels.
- 1,3 butadiene and benzene levels decrease as the ethanol concentration increases.
- Ethanol contains less sulfur than conventional fuels.

6.7.2 Disadvantages

- The chemical emulsifiers and ignition improvers used to blend ethanol may contain harmful chemicals.
- There are higher emissions of formaldehyde and acetaldehyde from ethanol vehicles than from diesel vehicles.
- There may be an odour problem.

7. Diesohol

7.1 *Background*

Diesohol is a fuel containing alcohol that comprises a blend of diesel fuel (84.5%), hydrated ethanol (15%) and an Australian developed emulsifier (0.5%). Hydrated ethanol is ethyl alcohol that contains approximately 5% water. The emulsifier is an important component in the preparation of the fuel. It has been developed in Australia by APACE Research.

In this chapter we examine ethanol (and hence diesohol) from wheat starch waste, as the buses that were tested in the diesohol tests whose results were used for the tailpipe emissions used diesohol with the ethanol made from wheat starch. However, we also present results that compare diesohol emissions with ethanol made from a range of different feedstocks.

7.2 *Full Fuel-Cycle Analysis of Emissions*

7.2.1 Greenhouse gas emissions

Figure 7.1 depicts the greenhouse gas emissions estimated for ethanol and diesohol. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

As may be expected, the addition of 15% of a renewable fuel, such as ethanol, to diesel reduces greenhouse gas emissions.

7.2.2 Particulate matter emissions

Figure 7.2 depicts the particulate matter (PM10) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate matter emissions using diesohol are lower than those using LSD.

7.2.3 Emissions of oxides of nitrogen

Figure 7.3 depicts the oxides of nitrogen (NOx) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

NOx emissions of diesohol are lower than NOx emissions of LSD.

7.2.4 Emissions of hydrocarbons

Figure 7.3 depicts the non-methanic hydrocarbon (HC) emissions estimated for diesel fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

HC emissions of diesohol are comparable with those of LSD.

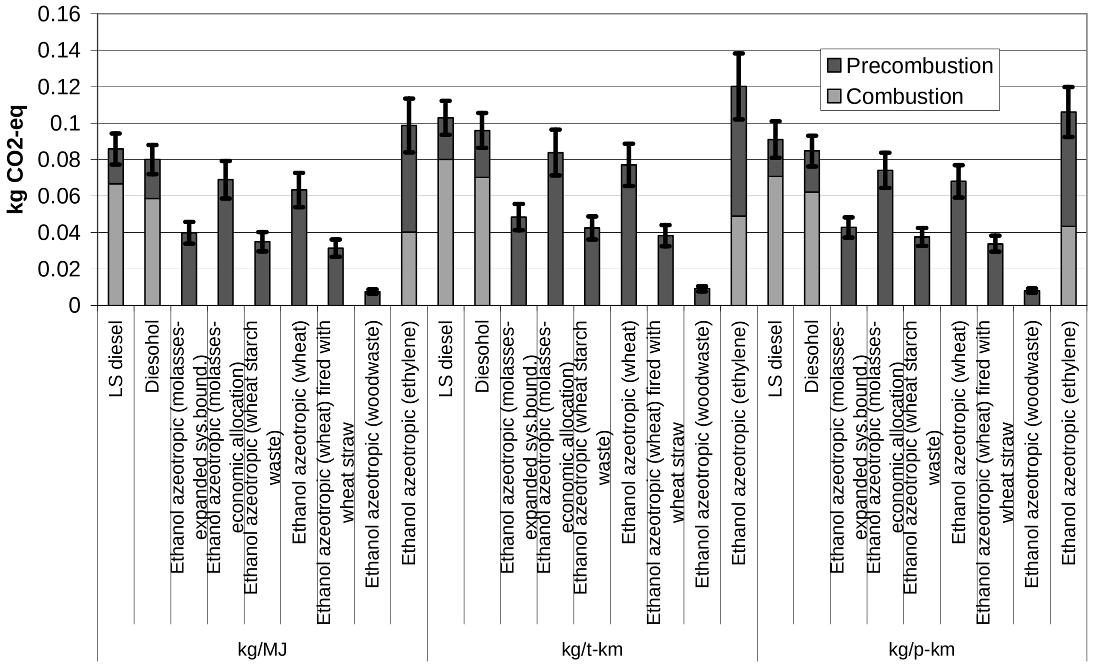

Figure 7.1
Exbodied emissions of greenhouse gases for diesohol and ethanol made from various sources.

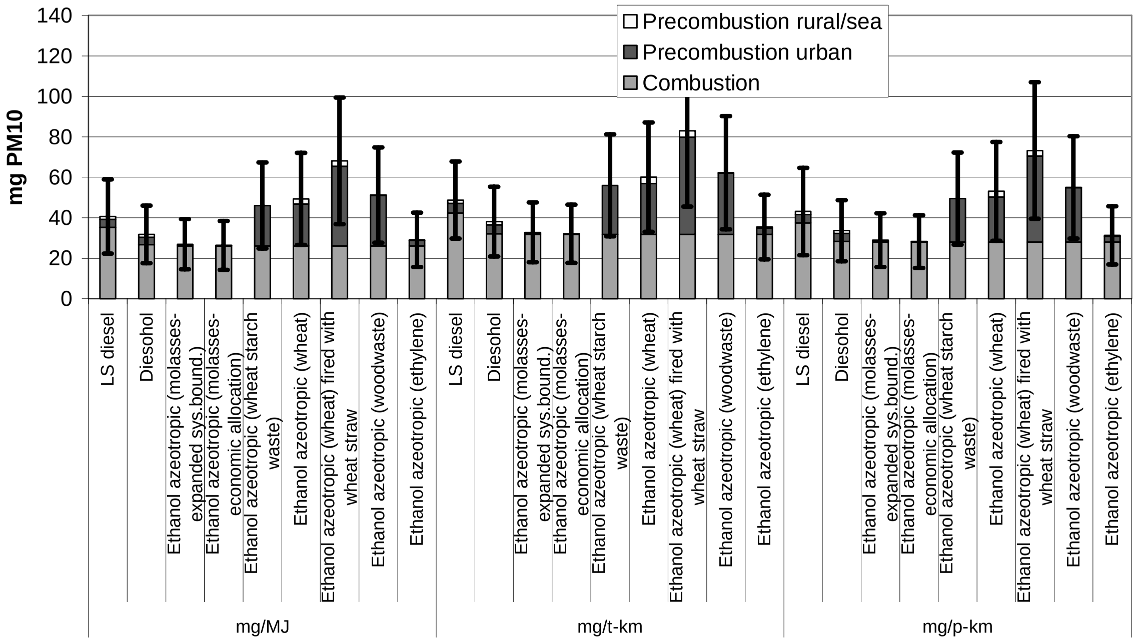

Figure 7.2
Exbodied emissions of particulate matter for diesohol and ethanol made from various sources.

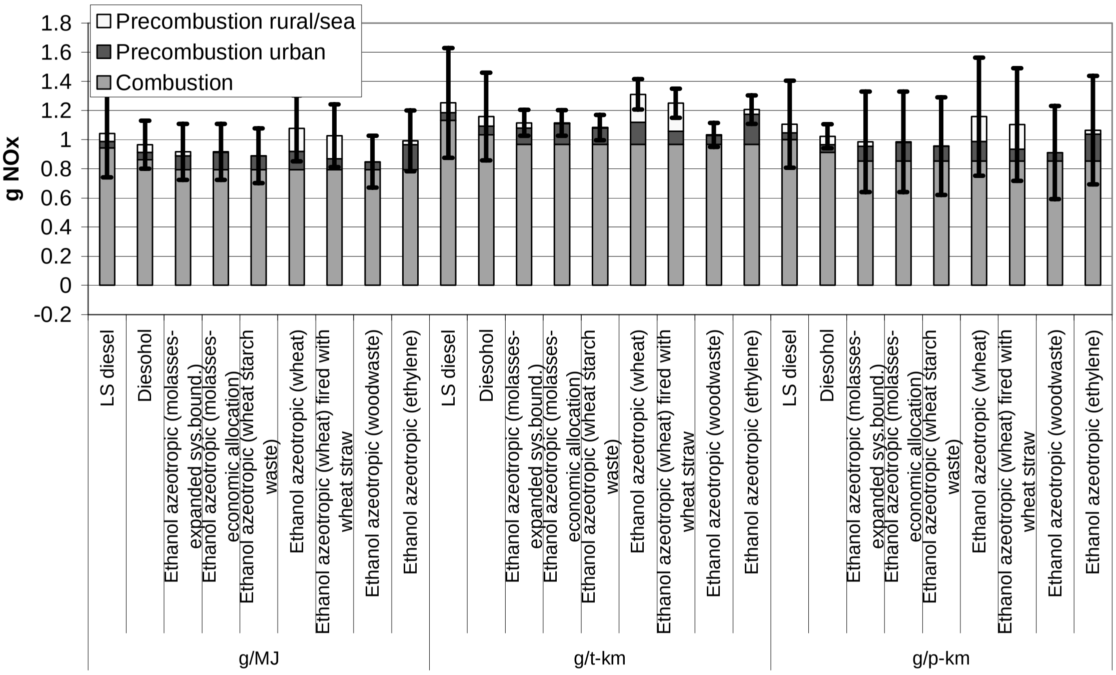

Figure 7.3
Exbodied emissions of oxides of nitrogen for diesohol and ethanol made from various sources.

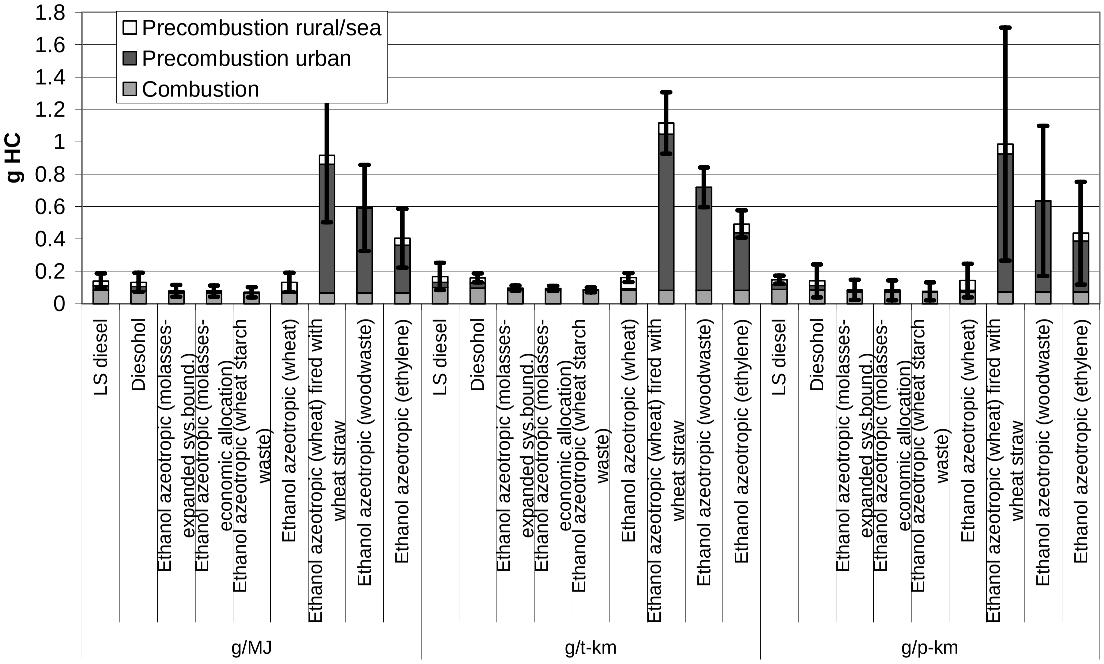

Figure 7.4
Exbodied emissions of hydrocarbons for diesohol and ethanol made from various sources.

7.3 Viability and Functionality

Problems may occur with the fuel injection equipment, and with the formation of vapour locks. Both can be easily remedied. Diesohol has passed stability test conducted by Shell. To date diesohol has been a niche fuel and thus the situation with respect to availability and warranty has not been clarified. During testing of buses using diesohol, the fuel was blended by delivering diesel to Manildra, near Nowra, and blending the diesel with ethanol and emulsifier.

7.4 Health and OH&S

As the composition of diesohol is 85% diesel the production and transport emissions associated with diesohol production are assumed to be similar to LSD. The LCA indicates that urban precombustion PM10 emissions of diesohol (39 mg/km or 3.63 mg/MJ) are marginally lower than LSD (43 mg/km or 4.0 mg/MJ), though the urban precombustion HC emissions are similar at 0.29 g/km or 0.026 g/MJ.

The LCA indicates that combustion PM emissions from diesohol (289 mg/km or 26.8 mg/MJ) are lower than LSD (380 mg/km or 35.3 g/MJ).

There is limited information available on air toxic emissions for diesohol. The high proportion of diesel in diesohol suggests that the air toxic emissions are unlikely to be substantially different to LSD, though tailpipe emissions of acrolein from diesohol appear to be lower than from diesel. The LCA indicates that HC combustion emissions of diesohol are similar to LSD.

The flash point and flammability characteristics of diesohol are those of alcohol. This requires that diesohol be considered and handled as gasoline (petrol) rather than as diesel fuel, even though the flash point of petrol is considerably lower than that of ethanol (13°C). In practical terms, APACE Research handles the fuel as it would ethanol to ensure safety.

7.5 Environmental issues

ESD issues

The environmental impact from the production of diesohol are the same as those from the production of the diesohol feedstocks; namely diesel and ethanol.

In particular, we draw attention to the fact that appropriate disposal of the refinery waste-products is crucial to environmental impacts or benefits. Dunder application is often criticised as being the cause of poor waste quality in Queensland, though there is little evidence of this (www.sunfish.org.au/fishkills/fishkills.htm). Conversely, appropriate and careful disposal of dunder means that many farmers in the district near Sarina now use it as a fertiliser and soil conditioner - even though it was once considered a poison.

Sustainability

Ethanol from sugar or wheat is liable to be a niche fuel and thus there are no sustainability issues associated with it. Large-scale usage of ethanol will require ligno-cellulosic production to be economical.

Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia's oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia's croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large-scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

Groundwater
We are not aware of any issues related to groundwater contamination.

7.6 ADR Compliance

Diesohol can be expected to meet all future Australian Design Rules for all pollutants except total hydrocarbon which may be slightly above Euro3 and Euro4 standards. APACE Research advises that vapour lock problems led to higher HC and CO emissions as reflected in Arcoumanis (2000). APACE has indicated that the addition of a booster pump now overcomes vapour lock and the resulting HC and CO problem which means that low sulfur diesohol should be able to meet all future ADRs.

7.7 Summary

7.7.1 Advantages

- Since it contains a renewable fuel component it produces less fossil CO_2 than conventional fuels.
- Particulate emissions are lowered.
- 1,3 butadiene and benzene levels decrease as the ethanol concentration increases.
- Less sulfur.

7.7.2 Disadvantages

- Overseas, the chemical emulsifiers used to blend ethanol and diesel contain harmful chemicals. According to APACE the chemical emulsifier that they use is composed only of hydrocarbons and oxygen and is thus no more harmful than diesel fuel.

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8. Compressed Natural Gas (CNG)

8.1 Background

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH_4). It is stored onboard a vehicle in a compressed gaseous state (CNG). Natural gas is distributed throughout Australia in extensive pipeline systems. A national fuel standard for CNG is to be developed in 2001-2002 under the *Fuel Quality Standards Act 2000.*

Most gas losses from the distribution systems are by way of leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters.

8.2 Results

Two modes of compression were examined: compression using natural gas and compression using electricity. The assumptions that are made in terms of methane losses, both upstream and during vehicle operation, determine whether one concludes that CNG (or LNG) emits more, or less, greenhouse gases. We assumed for Australia, on the basis of the advice received from stakeholders, that fugitive emissions are 0.1% of supply. This leads to the results, depicted below, that exbodied emissions of greenhouse gases are less than that of diesel. Earlier studies and overseas studies, based on assumptions of higher fugitive emissions, produce opposite results in relation to greenhouse gases. We undertook a sensitivity study, as depicted in Figure 8.3 of Part 2, that indicates that if fugitive emissions exceed approximately 4 % of supply then exbodied emissions of greenhouse gases exceed those of low sulfur diesel.

8.2.1 Greenhouse gas emissions

Figure 8.1 depicts the greenhouse gas emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116). An extra allowance of 400 kg for the weight of CNG tanks over diesel fuel tanks has been built into these figures.

Exbodied emissions of greenhouse gases are lower from CNG than from LSD under both scenarios.

8.2.2 Particulate matter emissions

Figure 8.2 depicts the particulate matter (PM10) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of CNG are markedly lower than those of LSD.

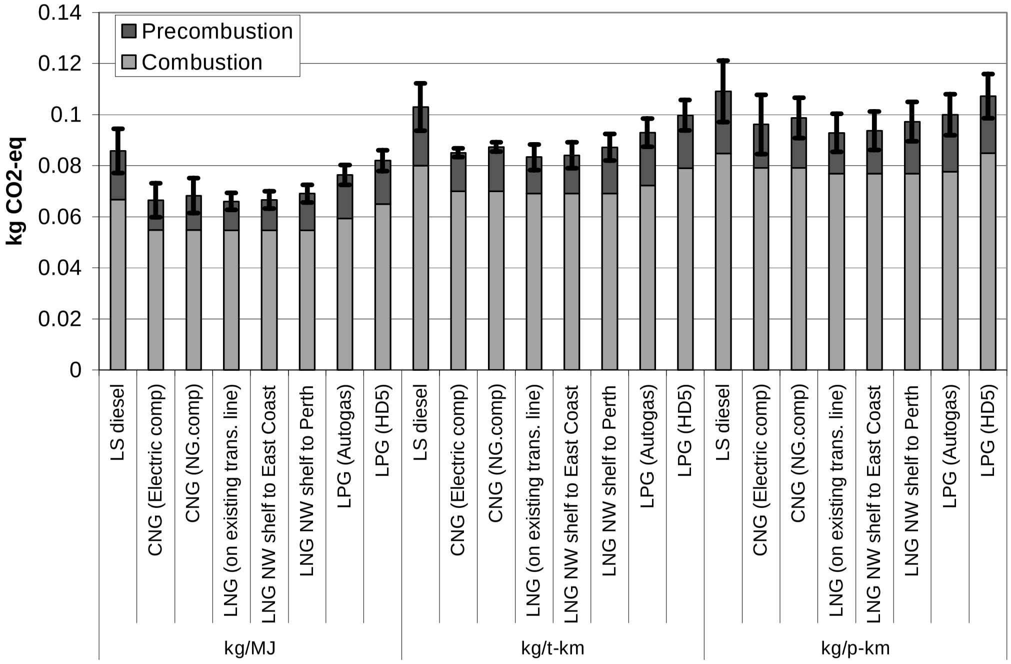

Figure 8.1
Exbodied emissions of greenhouse gases for gaseous fuels. The two CNG scenarios consist of gas compression and electric compression of the gas

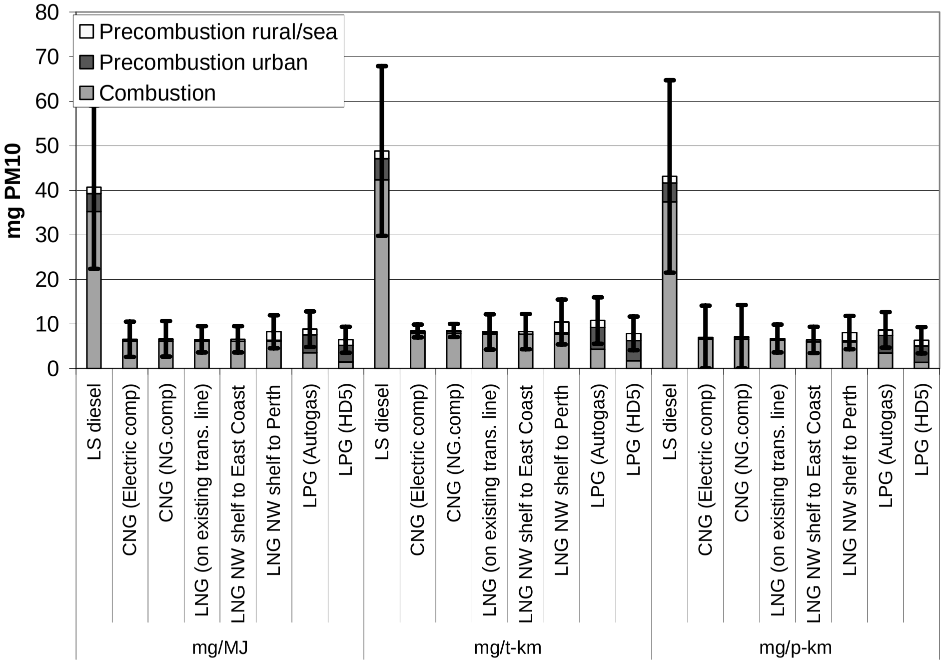

Figure 8.2
Exbodied emissions of particulate matter for gaseous fuels. The two CNG scenarios consist of gas compression and electric compression of the gas

8.2.3 Emissions of oxides of nitrogen

Figure 8.3 depicts the oxides of nitrogen (NOx) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. NOx emissions from CNG are lower than those of LSD.

8.2.4 Emissions of hydrocarbons

Emissions of hydrocarbons for the gaseous fuels are shown in Figure 8.4. In every case, the gaseous fuels have lower hydrocarbon emissions than low sulfur diesel, both on an upstream and tailpipe basis.

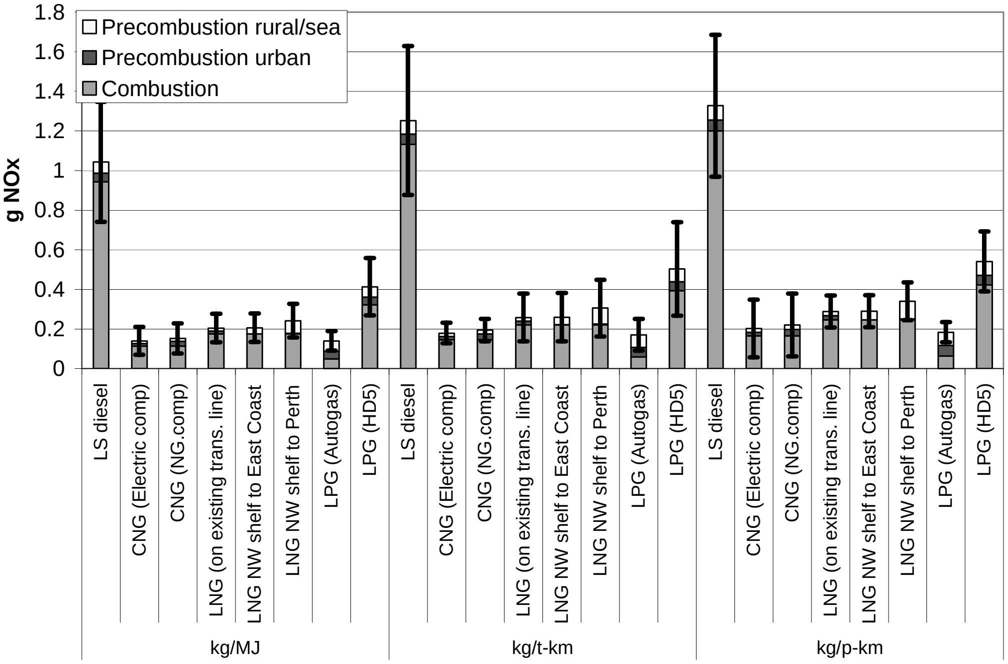

Figure 8.3
Exbodied emissions of oxides of nitrogen for gaseous fuels. The two CNG scenarios consist of gas compression and electric compression of the gas

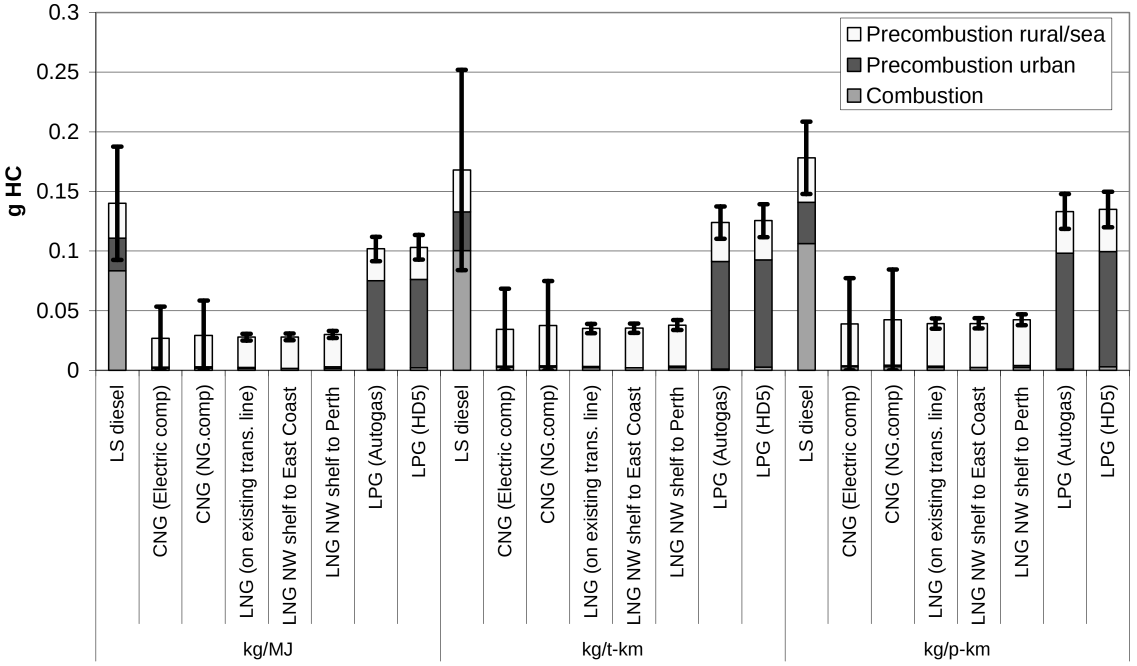

Figure 8.4
Exbodied emissions of hydrocarbons for gaseous fuels. The two CNG scenarios consist of gas compression and electric compression of the gas.

8.3 Viability and Functionality

Due to chronic problems with the engine and fuel system components (of the earlier generation of CNG engines) CNG buses in operation have had a significantly greater defect rate than diesel buses. The industry is confident that these problems have been overcome. Currently there are limited public CNG refuelling facilities, but the industry expects the number of facilities to more than double by the end of 2002.

Australian natural gas is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplies to Melbourne, and much of the rest of Victoria, were halted following the disaster at the Longford plant.

The majority of CNG vehicles in Australia were sourced as new vehicles. However, there has been growing interest in the conversion of conventionally fuelled vehicles to CNG through after-market conversions.

The emissions performance of converted Australian CNG vehicles is unclear due to a lack of comprehensive industry-wide data. The only results available were from one system that was used in a small number of vehicles. That system is currently being upgraded and is no longer sold in the previous configuration. Some tailpipe emissions from the previous configuration were much higher than those for OEM vehicles. It is possible that the difference in emission levels between converted vehicles and OEMs may decrease as the heavy duty vehicles conversion industry becomes more firmly established.

8.4 Health Issues

CNG upstream emissions of both particulate matter and air toxics are substantially less than LSD. CNG tailpipe emissions of particulate matter are substantially less than LSD. CNG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

On release to the atmosphere CNG is much lighter than air and thus it is safer than spilled diesel. In the case of a CNG leak, because of the gaseous nature of the fuel, the gas will issue as a very high velocity jet into the surroundings, aiding greatly in the rapid dispersion of the fuel.

8.5 Environmental Impact and Benefit

ESD *principles*

Noise levels from natural gas buses are less than those of diesel buses. CNG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of natural gas.

Sustainability

Natural gas is an indigenous fuel that could replace imported, expensive crude oil.

CNG can also be a renewable fuel for vehicles because it can be purified from the biogas extracted from waste treatment facilities.

Groundwater

Being a gaseous fuel, CNG does not impact groundwater.

8.6 ADR Compliance

CNG can be expected to meet all future Australian design rules for all pollutants.

8.7 Summary

8.7.1 Advantages

- CNG has very low particulate emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.

- It contains non-toxic components.
- It is much lighter than air and thus it is safer than spilled diesel.
- Methane is not a volatile organic compound (VOC).
- Engines fuelled with natural gas in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.

8.7.2 Disadvantages

- CNG on board a vehicle takes 3 to 4.5 times more volume for storage than diesel.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- The composition can vary widely depending on the CNG source, which affects stoichiometric air/fuel ratios.
- Its driving range is limited because its energy content per volume is relatively low as a result of its gaseous state.
- It requires special refuelling stations.
- The extra weight of the fuel tank leads to higher fuel consumption or loss of payload.
- Exhaust emissions of methane, which is a greenhouse gas, are relatively high compared with low sulfur diesel.
- It can give rise to backfire in the inlet manifold if the ignition system is faulty or fails in use.
- Relatively small fugitive emissions of methane can have a significant effect on the exbodied greenhouse gas emissions.

9. Liquefied Natural Gas (LNG)

9.1 Background

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH_4). LNG is generally refrigerated to –180°C for liquefaction, and requires vacuum-insulated cryogenic tanks to maintain it in liquid form for storage. Natural gas consumed in Australia is domestically produced from Australian oil and gas fields.

9.2 Results

Three LNG scenarios are examined. The base scenario (marked LNG) is that of piped movement of natural gas that is liquefied at central liquefaction plants. A shipping scenario (LNG to E. Coast) assumes that LNG from the Northwest Shelf is shipped to the East Coast of Australia. The road scenario (LNG to Perth) assumes that LNG is trucked (in LNG road trucks) to Perth from the Northwest Shelf.

9.2.1 Greenhouse gas emissions

Figure 9.1 depicts the greenhouse gas emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116). An extra allowance of 400 kg for the weight of LNG tanks over diesel fuel tanks has been built into these figures.

Exbodied emissions of greenhouse gases are lower from LNG than from LSD under all three scenarios.

9.2.2 Particulate matter emissions

Figure 9.2 depicts the particulate matter (PM10) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of LNG are markedly lower than those of LSD.

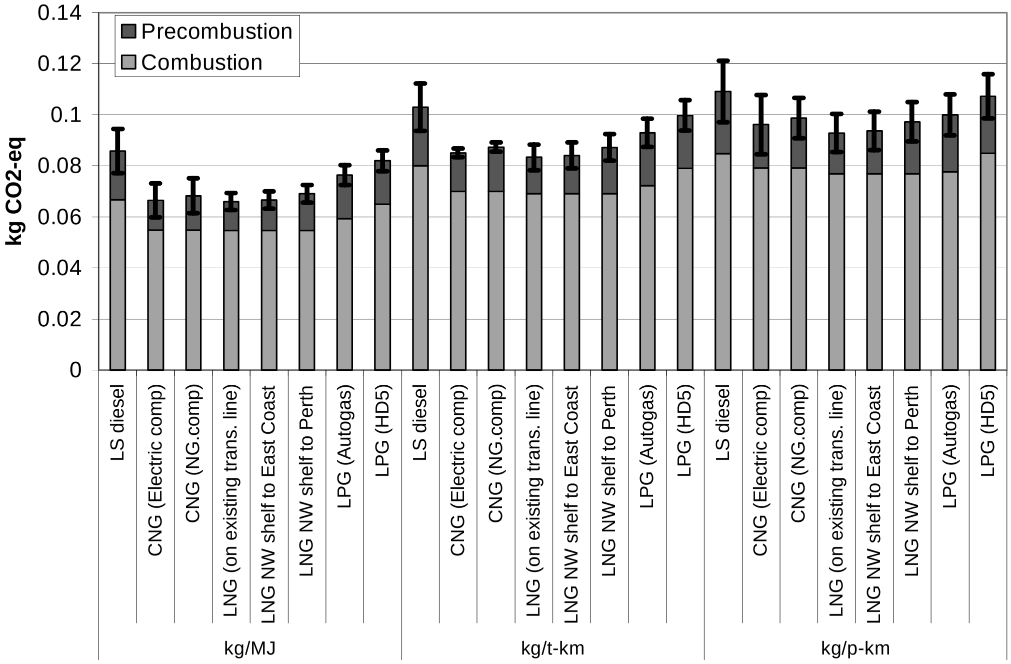

Figure 9.1
Exbodied emissions of greenhouse gases for gaseous fuels

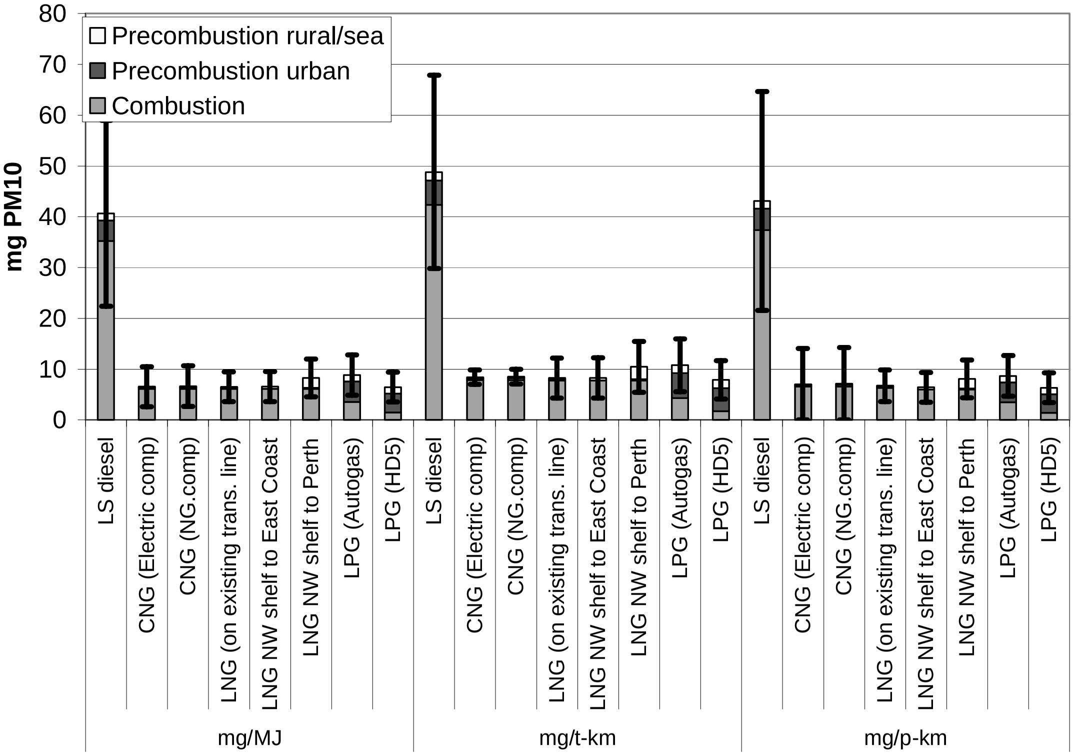

Figure 9.2
Exbodied emissions of particulate matter for gaseous fuels.

9.2.3 Emissions of oxides of nitrogen

Figure 9.3 depicts the oxides of nitrogen (NOx) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted.

LNG emissions of NOx are lower than those from LSD.

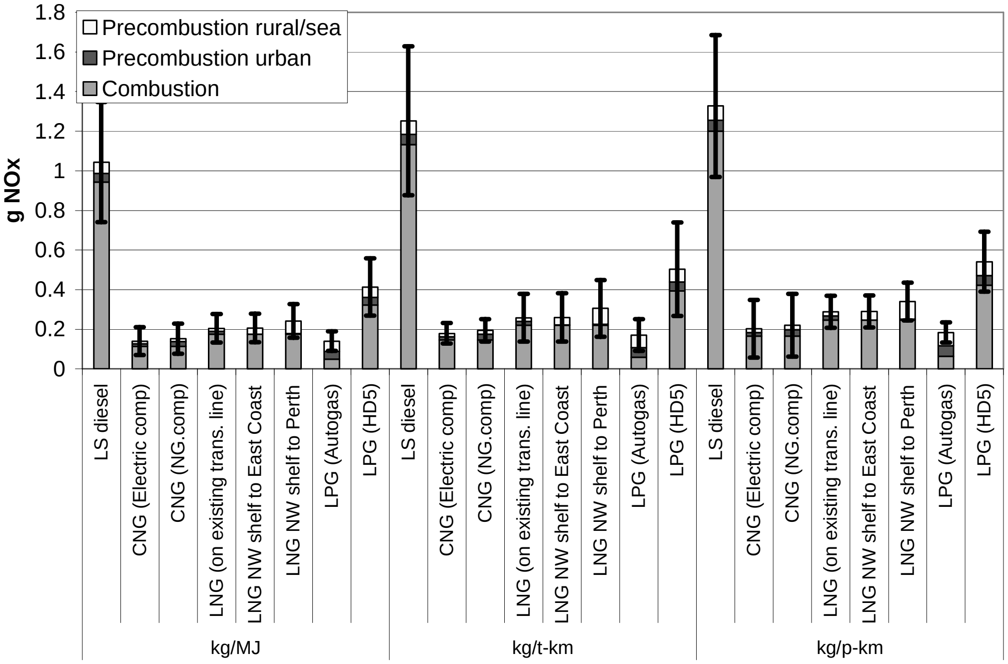

Figure 9.3
Exbodied emissions of oxides of nitrogen for gaseous fuels.

9.2.4 Emissions of hydrocarbons

Emissions of hydrocarbons for the gaseous fuels are shown in Figure 9.4. In every case, the gaseous fuels have lower hydrocarbon emissions than low sulfur diesel, both on an upstream and tailpipe basis.

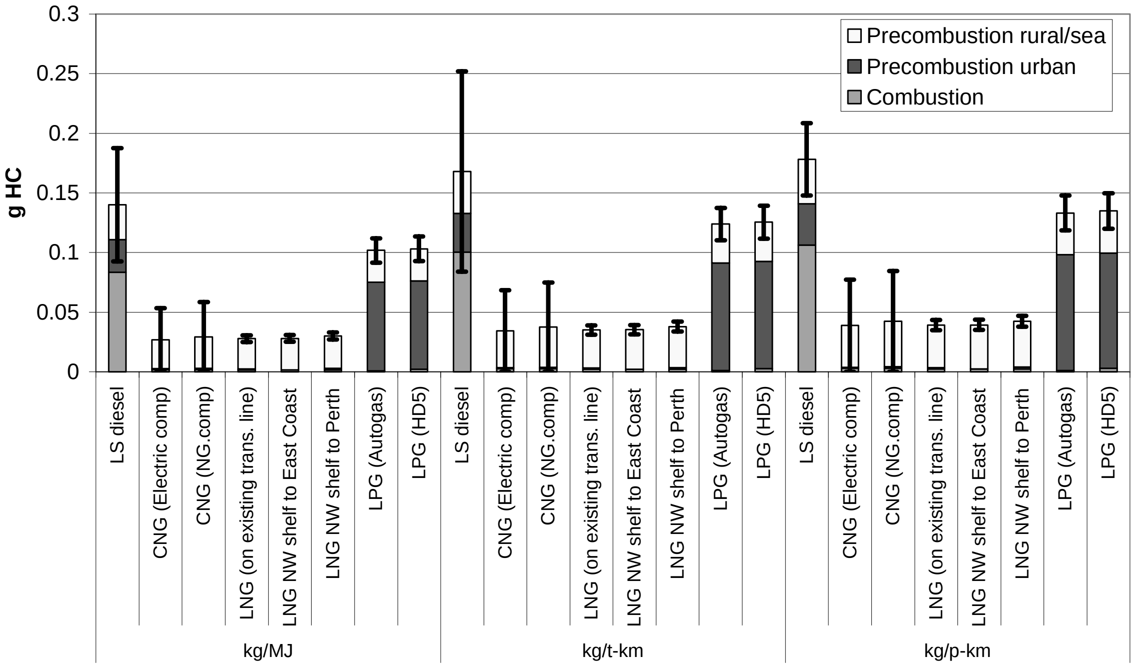

Figure 9.4
Exbodied emissions of hydrocarbons for gaseous fuels.

9.3 Viability and Functionality

LNG buses have the same reliability and operating cost issues as CNG buses. There were problems with earlier generations of heavy vehicle gas engines that appear to have been overcome. LNG vehicles have the advantage of less bulky fuel storage and longer vehicle operating range than CNG vehicles.

9.4 Health Issues

Emissions of particulate matter, some of which is carcinogenic, are almost eliminated with natural gas use. Lubricating oil appears to be the source of remaining particulate emissions. LNG upstream emissions of both particulates and air toxics are substantially less than LSD. LNG tailpipe emissions of particulates are substantially less than LSD. LNG tailpipe emission of THC as well as benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

When released to the atmosphere and evaporated LNG is much lighter than air and thus it is safer than spilled diesel.

9.5 Environmental Impact and Benefit

ESD principles

Noise levels from natural gas buses are less than those of diesel buses. LNG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of natural gas.

Sustainability

Natural gas is an indigenous fuel that could replace imported, expensive crude oil.

Groundwater

LNG is a gaseous fuel at normal temperature and pressure. Being a gaseous fuel, it does not impact groundwater.

9.6 ADR Compliance

LNG can be expected to meet all future Australian design rules for all pollutants.

9.7 Summary

9.7.1 Advantages

- LNG has very low particulate emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.
- It contains non-toxic components.
- When released to the atmosphere and evaporated it is much lighter than air and thus it is safer than spilled diesel.
- Methane is not a volatile organic compound (VOC).
- Engines fuelled with natural gas in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.

9.7.2 Disadvantages

- There is considerable extra infrastructure involved with gas liquefaction.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- Its driving range is limited because its energy content per volume is relatively low as a result of its gaseous state.
- It requires special refuelling stations and handling of a cryogenic liquid making it suitable only for fleet operations.
- The energy required to liquefy natural gas leads to increased greenhouse gas emissions in comparison to CNG.
- Exhaust emissions of methane, which is a greenhouse gas, are relatively high compared with low sulfur diesel.
- Refuelling time typically is longer than that of diesel.
- It can give rise to backfire in the inlet manifold if the ignition system is faulty or fails in use.

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10. Liquefied Petroleum Gas (LPG) - Autogas

10.1 Background

Liquefied petroleum gas (LPG) a petroleum industry by-product, consists mainly of propane, propylene, butane, and butylene in various proportions according to its State of origin. Autogas grade LPG is a mixture of propane and butane in approximately equal ratios. The Australian industry has prepared a set of performance-based specifications that are widely seen as a de facto standard. LPG has particularly low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost. A national standard for LPG is being developed under the *Fuel Quality Standards Act 2000*.

10.2 Full Fuel Cycle Results

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics though there is considerable data in relation to LPG used in cars. The AGO also has some data on dual fuel vehicles as a result of the Alternative Fuels Conversion Program.

10.2.1 Greenhouse gas emissions

Figure 10.1 depicts the greenhouse gas emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

Exbodied emissions of greenhouse gases are lower from Autogas than from LSD.

10.2.2 Particulate matter emissions

Figure 10.2 depicts the particulate matter (PM10) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of Autogas are markedly lower than those of LSD.

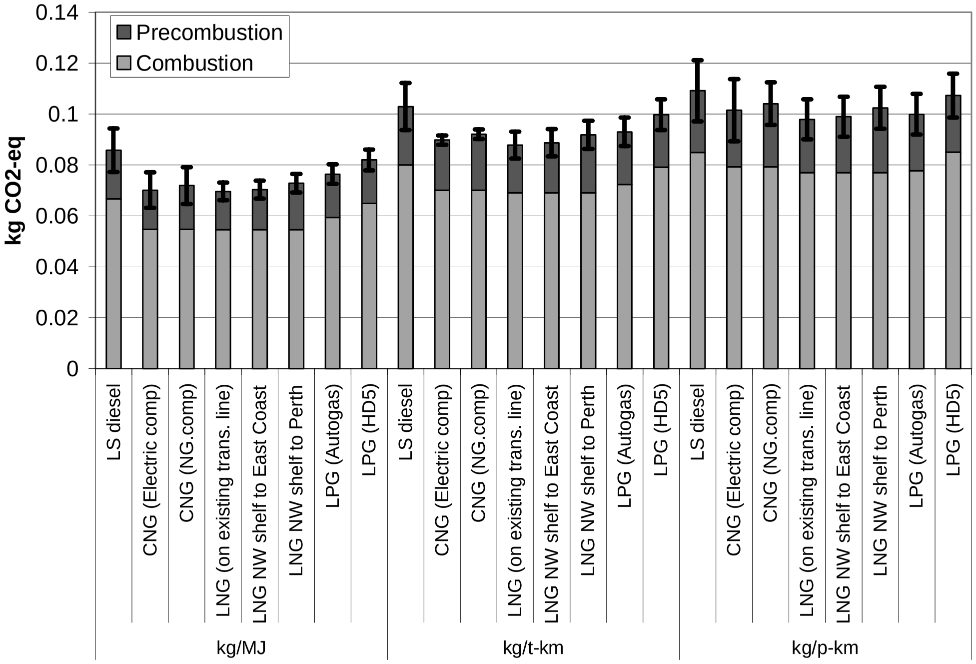

Figure 10.1
Exbodied emissions of greenhouse gases for gaseous fuels.

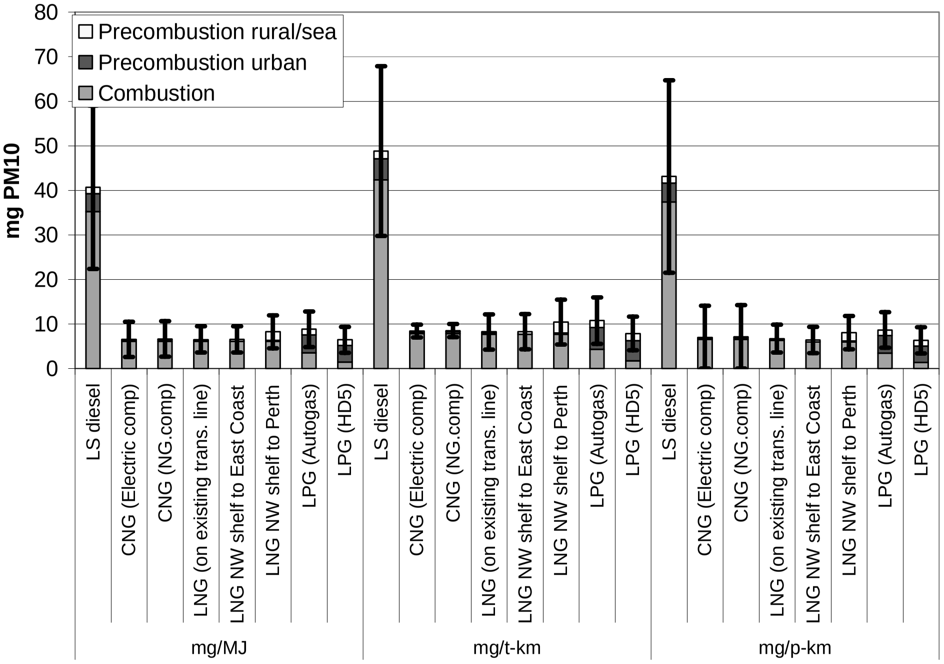

Figure 10.2
Exbodied emissions of particulate matter for gaseous fuels.

10.2.3 Emissions of oxides of nitrogen

Figure 10.3 depicts the oxides of nitrogen (NOx) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Emissions of NOx from Autogas are lower than those of LSD.

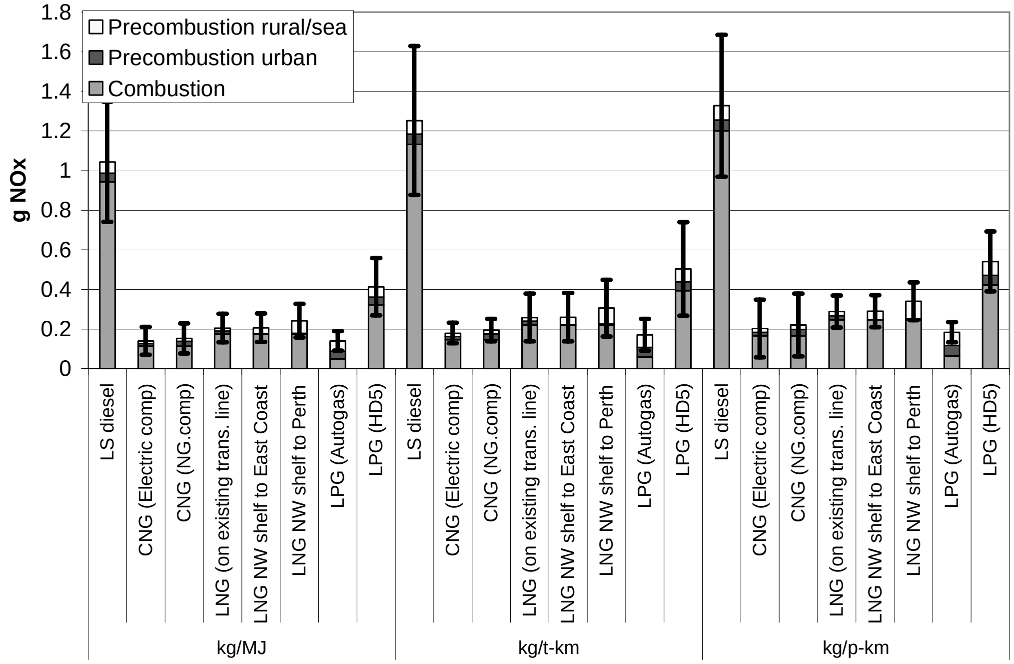

Figure 10.3
Exbodied emissions of oxides of nitrogen for gaseous fuels.

10.2.4 Emissions of hydrocarbons

Emissions of hydrocarbons for the gaseous fuels are shown in Figure 10.4. In every case, the gaseous fuels have lower exbodied hydrocarbon emissions than LSD, though we estimate larger pre-combustion emissions of hydrocarbons from autogas than from LSD, primarily as a result of leakage.

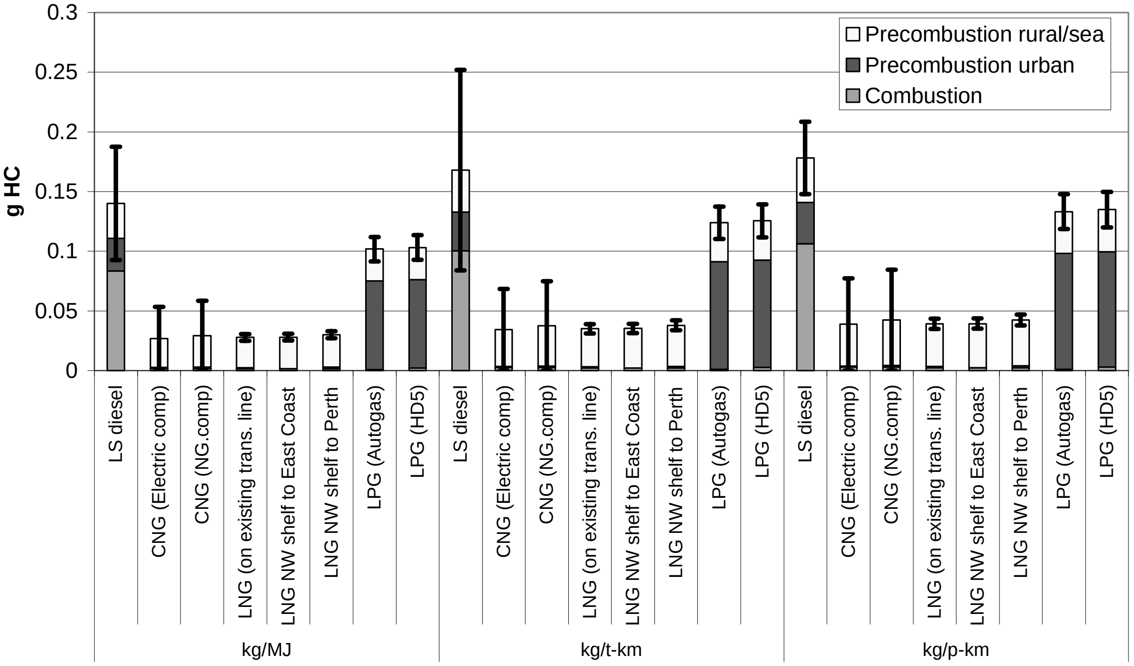

Figure 10.4
Exbodied emissions of hydrocarbons for gaseous fuels

10.3 *Viability and Functionality*

DAF, the Dutch vehicle maker, developed a dedicated LPG fuelled bus using the stoichiometric process rather than lean burn. This process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2.

Some ullage space must be left in an LPG tank because the liquid volume expands significantly if the tank encounters increasing ambient temperatures. Gaseous fuelled engines are generally considered easier to start than petrol or diesel engines in cold weather, because the fuel is vaporized before injection into the engine. Hot starting may, however, produce difficulties.

Australian LPG, being primarily sourced from natural gas, is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplied to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. During the period of gas shortage, LPG was sourced from interstate and there was, in fact, no disruption to supply. The NSW cavern storage of LPG at Port Botany provides added security.

Presently there are no data on emissions from diesel vehicles converted to use autogas. It is expected that the performance of such converted vehicles will be similar to vehicles that have been converted to use propane (LPG-HD5). These are dealt with in the next chapter.

10.4 Health Issues

LPG's low emissions have low greenhouse gas effects and low NOx precursors. LPG upstream emissions of particulate matter are similar to LSD. LPG upstream emissions of air toxics are greater than LSD. LPG tailpipe emissions of particulate matter are substantially less than LSD. LPG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

LPG vapor is heavier than air, disperses slowly, and can accumulate in local valleys. LPG, when involved in a leak will discharge in a liquid form requiring a period of time to vaporize and disperse. LPG fires tend to persist within the leakage area due to its liquid and heavier than air state. For fuel line ruptures, pressurized gaseous fuels represent higher hazard levels than petrol.

10.5 Environmental Issues

The environmental issues surrounding LPG are the same as those for CNG and LNG, in that they are gaseous fuels that do not cause land or water pollution. Air pollutants are reduced when compared to LSD. Dedicated LPG vehicles have lower emissions than dual-fuelled vehicles.

ESD principles

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

Sustainability

LPG is an indigenous fuel that could replace imported, expensive crude oil.

Groundwater

Being a gaseous fuel, LPG does not impact groundwater.

10.6 ADR Compliance

LPG can be expected to meet all future Australian Design Rules for all pollutants.

10.7 Summary

10.7.1 Advantages

- It has low cold-start emissions due to its gaseous state.
- It has lower peak pressure during combustion, which generally reduces noise and improves durability; noise levels can be less than 50% of equivalent diesel engines.
- LPG fuel systems are sealed and evaporative losses are negligible.
- It is easily transportable and offers 'stand-alone' storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- It contains negligible toxic components.

- LPG has lower particulate emissions and lower noise levels relative to diesel, making it more attractive for urban areas.
- Its low emissions have low greenhouse gas effects and low NOx precursors.
- Relative to other fuels, any increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

10.7.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low which explains why LPG tanks take more space than diesel fuel tanks.
- The LPG tanks are pressure vessels and therefore weigh more than diesel tanks.
- It is heavier than air, which requires appropriate handling.
- Its vapour flammability limits in air are wider than those of petrol, which makes LPG ignite more easily.
- It has a high expansion coefficient so that tanks can only be filled to 80% of capacity.
- LPG in liquid form can cause cold burns to the skin in case of inappropriate use.

11. Liquefied Petroleum Gas (LPG) – HD5

11.1 Background

LPG HD-5 is essentially liquefied propane gas. Most LPG used on the East Coast of Australia is Autogas. Propane as a vehicle fuel is limited to Western Australia. There is very little usage of LPG in Australian heavy vehicles. LPG has particularly low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost.

11.2 Results

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics though there is considerable data in relation to LPG used in cars.

11.2.1 Greenhouse gas emissions

Figure 11.1 depicts the greenhouse gas emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116). Exbodied emissions of greenhouse gases are lower from HD5 than from LSD.

11.2.2 Particulate matter emissions

Figure 11.2 depicts the particulate matter (PM10) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Particulate emissions of HD5 are markedly lower than those of LSD.

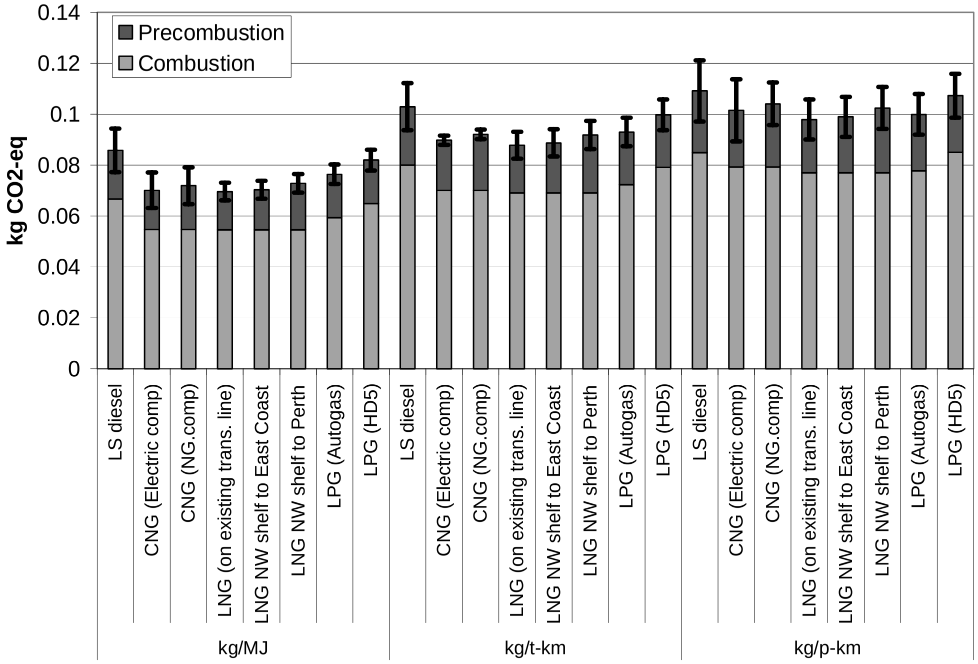

Figure 11.1
Exbodied emissions of greenhouse gases for gaseous fuels.

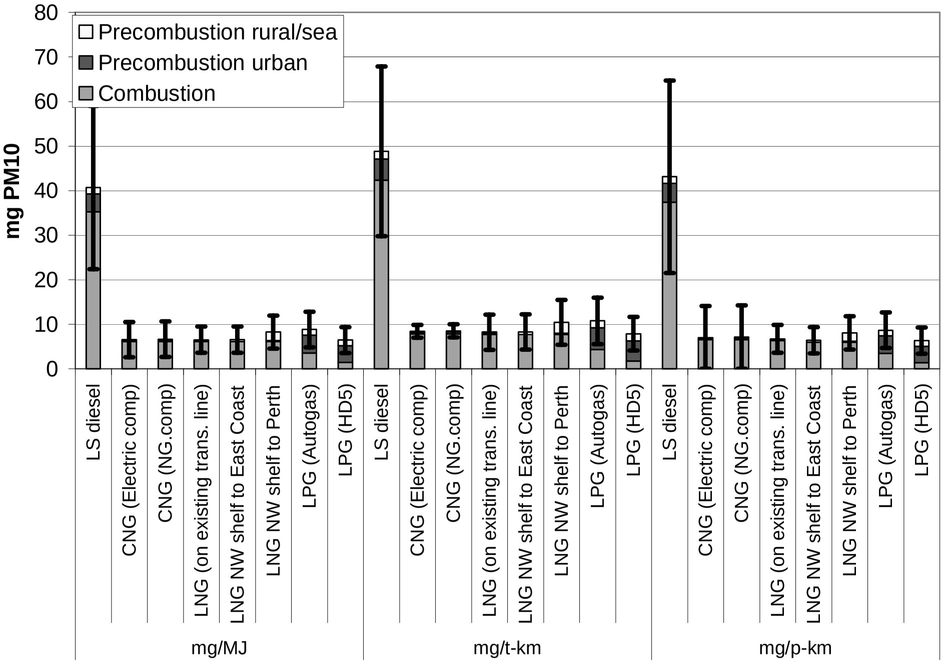

Figure 11.2
Exbodied emissions of particulate matter for gaseous fuels.

11.2.3 Emissions of oxides of nitrogen

Figure 11.3 depicts the oxides of nitrogen (NOx) emissions estimated for gaseous fuels. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Emissions of NOx from HD5 are lower than those of LSD.

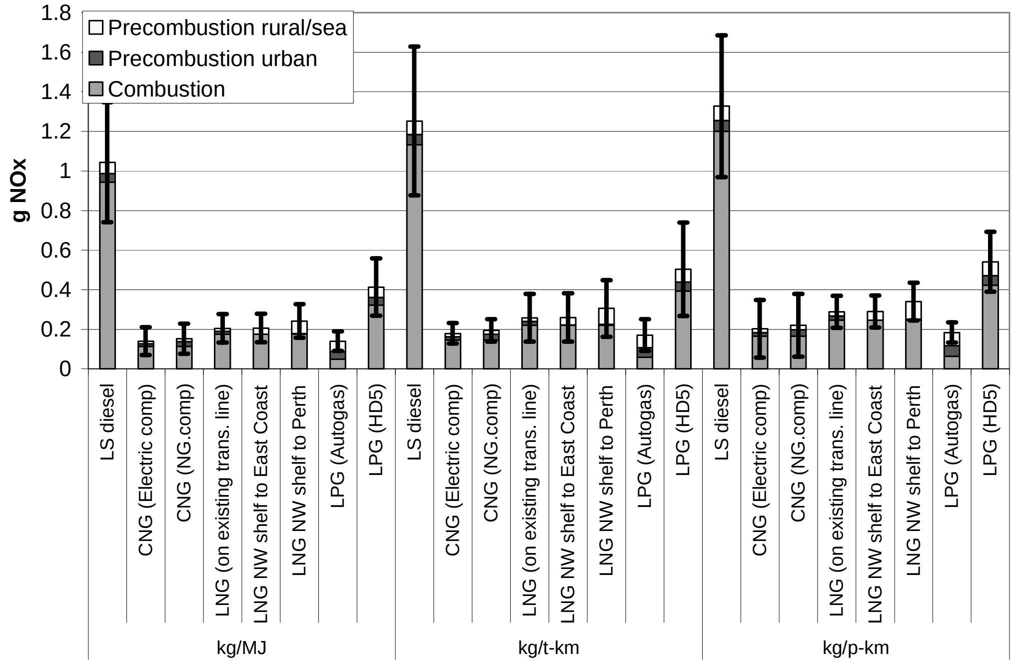

Figure 11.3
Exbodied emissions of oxides of nitrogen for gaseous fuels.

11.2.4 Emissions of hydrocarbons

Emissions of hydrocarbons for the gaseous fuels are shown in Figure 11.4. In every case, the gaseous fuels have lower exbodied hydrocarbon emissions than LSD, though we estimate large pre-combustion emissions of hydrocarbons from propane primarily from leakage.

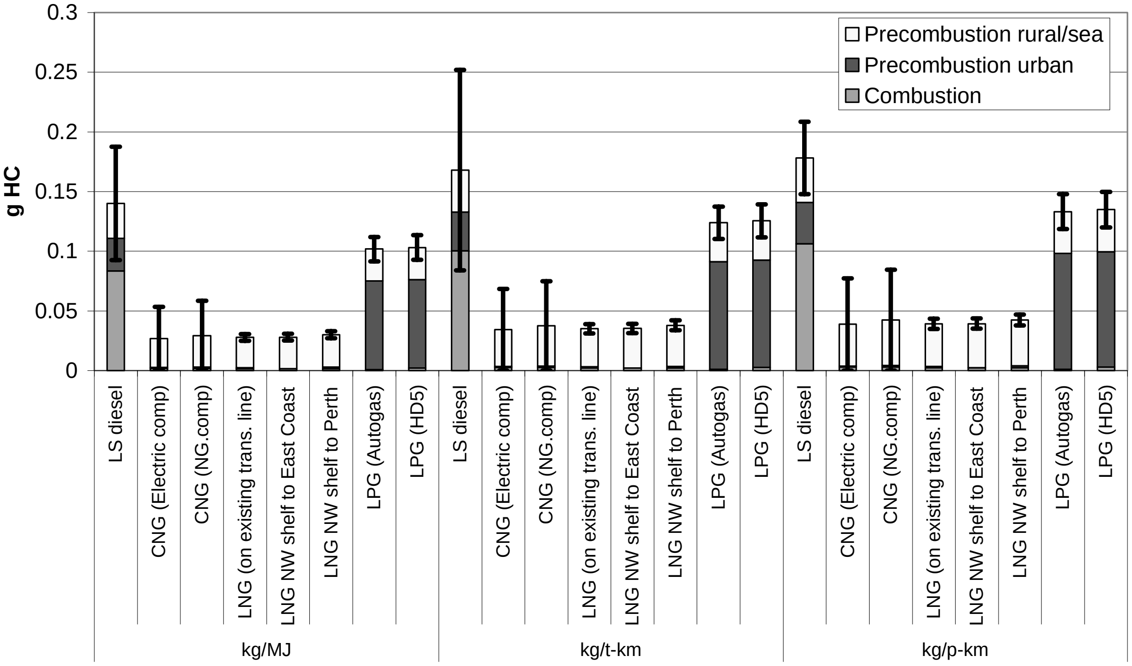

Figure 11.4
Exbodied emissions of hydrocarbons for gaseous fuels

11.3 Viability and Functionality

Propane (HD5) viability and functionality issues are identical to those of Autogas. The main benefit of propane is that the vehicle compression ratio can be adjusted to make use of the higher octane fuel and thus improve fuel economy.

Stakeholder input from Cummins noted that when comparing diesel, propane and natural gas in the same engine then the engine performance ratings are highest for diesel, then CNG, then propane.

Kleenheat Gas recently developed a diesel/LPG fuel substitution conversion kit that was used in a trial of an articulated Volvo B10M MkIII LPG bus in Darwin. Was Diesel Now Gas offers conversion to a dedicated HD-5 vehicle. From the very limited data available, vehicles converted to LPG appear to be less successful at reducing emissions than newly purchased LPG vehicles. Converted vehicles appear to have higher tailpipe emission of hydrocarbons than diesel vehicles, though particulate matter emissions are lower. Other emissions affecting air quality appear to be similar to those of diesel while emissions of carbon dioxide are similar to, or slightly less than, those of similar diesel vehicles. However, it should be reiterated that these conclusions are based on the testing of one converted dual fuel vehicle and one vehicle converted from diesel to dedicated LPG-HD5. The Australian LPG conversion industry for heavy vehicles is at an early stage in its development and the data from such test may not reflect the emissions performance of converted vehicles in the longer term.

DAF, the Dutch vehicle maker, has developed a dedicated LPG fuelled bus using the stoichiometric process rather than lean burn. This process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2.

Some ullage space must be left in an LPG tank because the liquid volume expands significantly if the tank encounters increasing ambient temperatures. Gaseous fuelled engines are generally considered easier to start than petrol or diesel engines in cold weather, because the fuel is vaporized before injection into the engine. Hot starting may, however, produce difficulties.

Australian LPG, being primarily sourced from natural gas, is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplied to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. During the period of gas shortage, LPG was sourced from interstate and there was no disruption to the LPG supply. The NSW cavern LPG storage facility at Port Botany provides added security.

11.4 Health Effects

Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles. LPG in liquid form can cause cold-burns to the skin in case of inappropriate use. In general, the health effects of Autogas and HD5 are the same.

LPGHD5 upstream emissions of particles are similar to LSD. LPGHD5 upstream emissions of air toxics are greater than LSD. LPGHD5 tailpipe emissions of particles are substantially less than LSD. LPGHD5 tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

11.5 Environmental Issues

Air pollutants are reduced when compared to LSD. Dedicated LPG vehicles have lower emissions than dual-fuelled vehicles. When compared to Autogas, HD5 produces more NOx but less particulate matter.

ESD principles

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

Sustainability

LPG is an indigenous fuel that could replace imported, expensive crude oil.

Groundwater

Being a gaseous fuel, LPG does not impact groundwater.

11.6 ADR Compliance

LPG can be expected to meet all future Australian Design Rules for all pollutants.

11.7 Summary

11.7.1 Advantages

- Propane has low cold-start emissions due to its gaseous state.
- Propane has lower peak pressure during combustion than conventional fuels, which generally reduces noise and improves durability.
- LPG fuel systems are sealed and evaporative losses are negligible.
- Propane is easily transportable and offers 'stand-alone' storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- Propane contains negligible toxic components.
- LPG has lower particulate emissions and lower noise levels relative to diesel, making propane attractive for urban areas. Noise levels can be less than 50% of equivalent engines using diesel.
- Propane's emissions are low in greenhouse gases and low in NOx, thus they are low in ozone precursors.
- Increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

11.7.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low which explains why LPG tanks take more space than diesel fuel tanks of the same energy storage capacity.
- Propane tanks are pressure vessels and thus weigh more than the equivalent diesel tank.
- Propane is heavier than air, which requires appropriate handling.
- Propane vapour flammability limits in air are wider than those of petrol, which makes LPG ignite more easily.
- Propane has a high expansion coefficient so that tanks can only be filled to 80% of capacity.
- Propane in liquid form can cause cold burns to the skin in case of inappropriate use.

12. Premium Unleaded Petrol Summary

12.1 Introduction

The study brief requires an examination of Premium Unleaded petrol (PULP), which is a 95 RON fuel meeting either the Euro II specification for unleaded petrol or the fuel specifications for PULP proposed by the Commonwealth for implementation in 2002. It is assumed that this fuel does not contain ethanol and that it is used in light vehicles as defined in ADR 79/00 and 79/01. Our analysis treats PULP as a reference fuel against which to compare ethanol blends. Our analysis is thus based on a hypothetical vehicle that satisfies Euro 2 tailpipe emissions.

The difference between ULP and PULP is determined by differences in octane rating. PULP blend typically contains larger proportion of high octane streams, i.e those containing aromatics, isoparaffins and naphthenes.

Upstream emissions in petrol production arise from oil recovery, transportation and processing. Further emissions derive from the distribution through the retail network.

12.2 Results

Because PULP is treated as a reference fuel, its results are used as a basis of comparison for petrohol and for anhydrous ethanol in the following chapters.

12.3 Viability and Functionality

Petrol is the most common automotive fuel, and unleaded petrol has been in use in Australia since 1986. Manufacturers produce premium unleaded petrol and its use does not cause warranty problems. Vehicle operational range depends on the size of the fuel tank, but typical values for a four or six cylinder car range from 400 to 600 km.

All forms of petrol are considered hazardous according to Worksafe Australia criteria, more so than diesel fuel. Petrol has an extreme flammability rating and extreme chronic effect rating. It has moderate toxicity and body contact ratings.

12.4 Health Issues

A typical material data safety sheet will note that unleaded petrol is highly flammable; harmful by inhalation, in contact with skin and if swallowed; possibly carcinogenic; and may cause damage to health from prolonged exposure.

12.5 Environmental Impact and Benefits

ESD

Ecologically sustainable development (ESD) is based on the principles of equity, efficiency and ecological integrity. The modern western economy is based on petroleum products, of which petrol, unleaded petrol, and premium unleaded petrol are examples. Though substantial arguments can be advanced that such an economy is not sustainable, in the sense that fossil fuels constitute a non-renewable resource, over the past three decades exploration activity has continually discovered new hydrocarbon reserves. In addition, the current concern over climate change has highlighted the burning of fossil fuels as one of the main causes. Thus even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity.

Sustainability

The sustainability of petrol depends on the sustainability of the crude oil from which it is refined. Australian oil reserves are, or soon will be in decline. There will either be increased reliance on imports or there will need to be fuel substitution. This means that sustainability of petrol is dependent on global oil supplies.

Groundwater contamination

Petrol is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from petrol itself can also occur, especially from leaks, at service stations and refuelling depots, which have been known to contaminate groundwater supplies.

13. Anhydrous Ethanol

13.1 Background

Anhydrous ethanol can be used as an additive in petrol, or as a fuel in its own right. Despite this, as an automotive fuel it is usually composed of 85% ethanol with 15% petrol (E85P) and this is the fuel that will be examined in this chapter. The reason for this is that the addition of 15% petrol improves the ignitability of alcohol, especially at low temperature. Other additives have also been trialled as ignition improvers. Ethanol is probably the most widely used alternative automotive fuel in the world, mainly due to Brazil's decision to produce fuel alcohol from sugar cane.

13.2 Results

The upstream emissions associated with anhydrous ethanol are essentially the same as those associated with hydrated ethanol, with a requirement for extra energy input arising from the extra process step to transform the hydrated ethanol to anhydrous ethanol. According to Table 10 of the chapter on hydrated ethanol, 30% more energy is needed to convert hydrated ethanol to anhydrous ethanol. Our calculations also include the emissions associated with the production of the 15% of petrol added to the anhydrous ethanol. We have taken tailpipe emissions as being those from a representative car, and compare E85P against PULP.

13.2.1 Greenhouse gas emissions

Figure 13.1 depicts the greenhouse gas emissions estimated for the reference fuel (PULP) for light vehicles, and for anhydrous ethanol (E85P). These are shown as emissions on an energy basis, and as emissions per kilometre for a car.

Exbodied greenhouse gas emissions of E85P are approximately half those of PULP, or less, depending on the fuel source provided it is sourced from renewable material. Ethanol manufactured from fossil fuels emits more greenhouse gases than petrol.

13.2.2 Particulate matter emissions

Figure 13.2 depicts the particulate matter (PM10) emissions estimated for PULP and E85P. These are shown as emissions on an energy basis, as emissions on a per km basis for cars. Emissions from PULP are generally comparable to those from E85D, though if waste (wheat waste or wood waste) is used as a combustion source (instead of natural gas) then the particles emitted during the upstream phases mean that the exbodied particulate matter emissions are greater than those from PULP.

13.2.3 Emissions of oxides of nitrogen

Figure 13.3 depicts the oxides of nitrogen (NOx) emissions estimated for E85P and PULP. These are shown as emissions on an energy basis, and as emissions on a per km basis for cars. NOx emissions from E85P, in comparison with those of PULP, are very variable. The exact nature of the process and the assumptions made in terms of life-cycle allocations are crucial in determining whether the E85P emissions of NOx are less than those of PULP (which occurs when waste material is used), or greater than those of PULP (which occurs when fossil fuels or non-waste material are used).

13.2.4 Emissions of hydrocarbons

Figure 13.3 depicts the non-methanic hydrocarbon (HC) emissions estimated for PULP and E85P. These are shown as emissions on an energy basis, and as emissions on a per km basis for cars. PULP. If natural gas is used to fire the plant then exbodied HC emissions of E85P are comparable to, or possibly slightly below, those of PULP. If wheat or wood is used as an energy source, or if fossil fuels are used to make the ethanol, then HC emissions are greater than those from PULP.

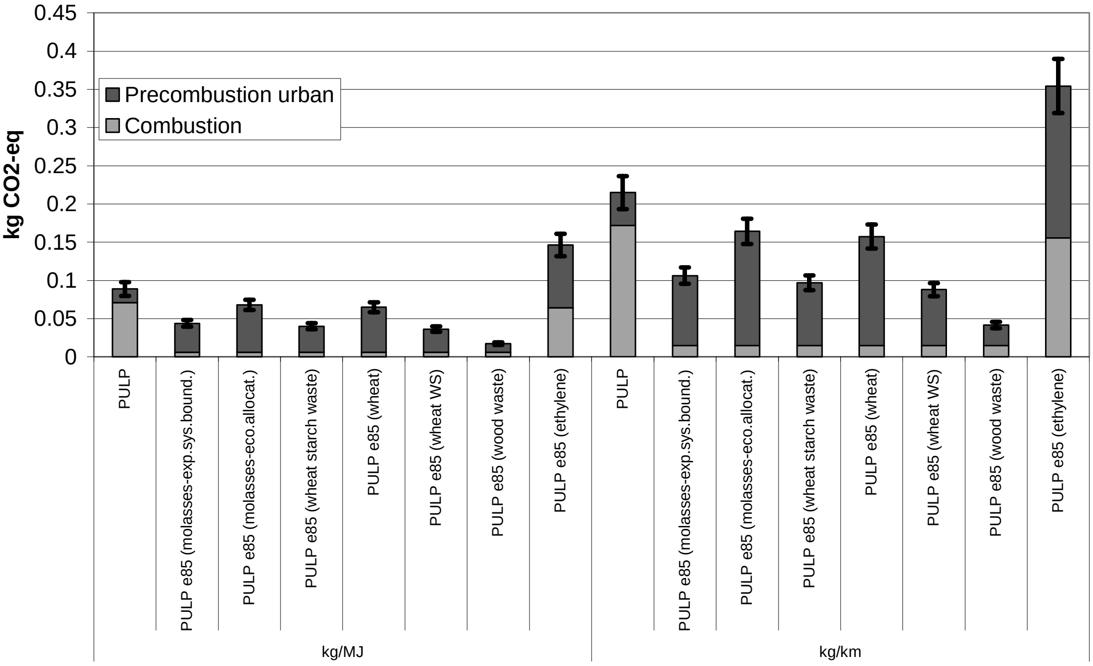

Figure 13.1
Exbodied emissions of greenhouse gases for premium unleaded petrol and anhydrous ethanol (E85P).

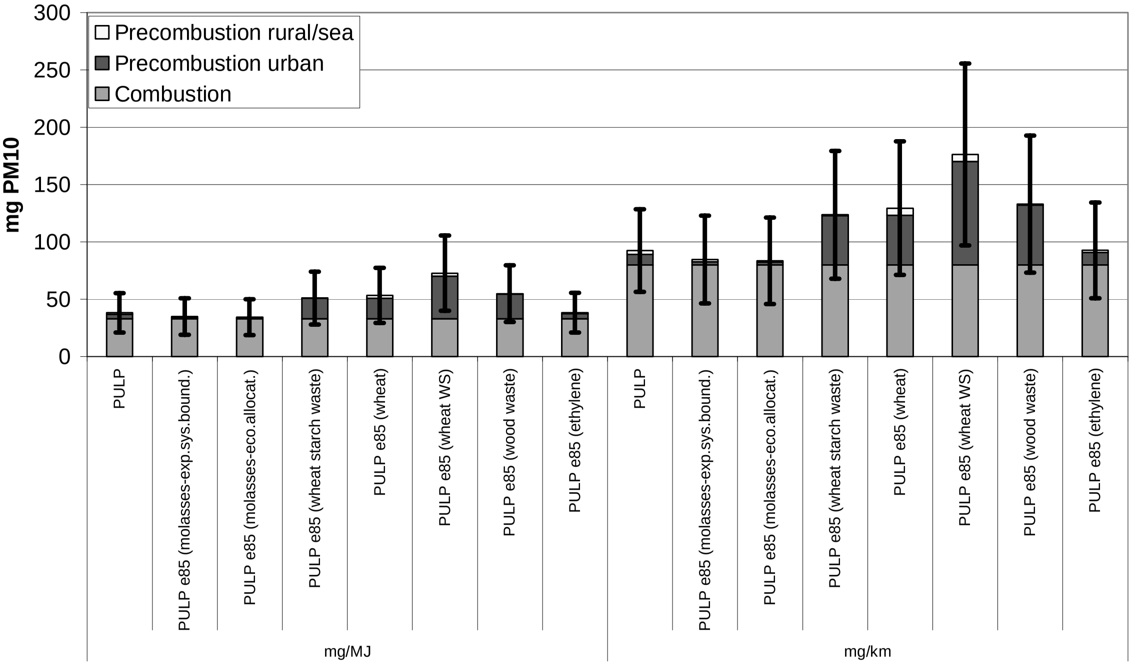

Figure 13.2
Exbodied emissions of particulate matter for premium unleaded petrol and anhydrous ethanol (E85P).

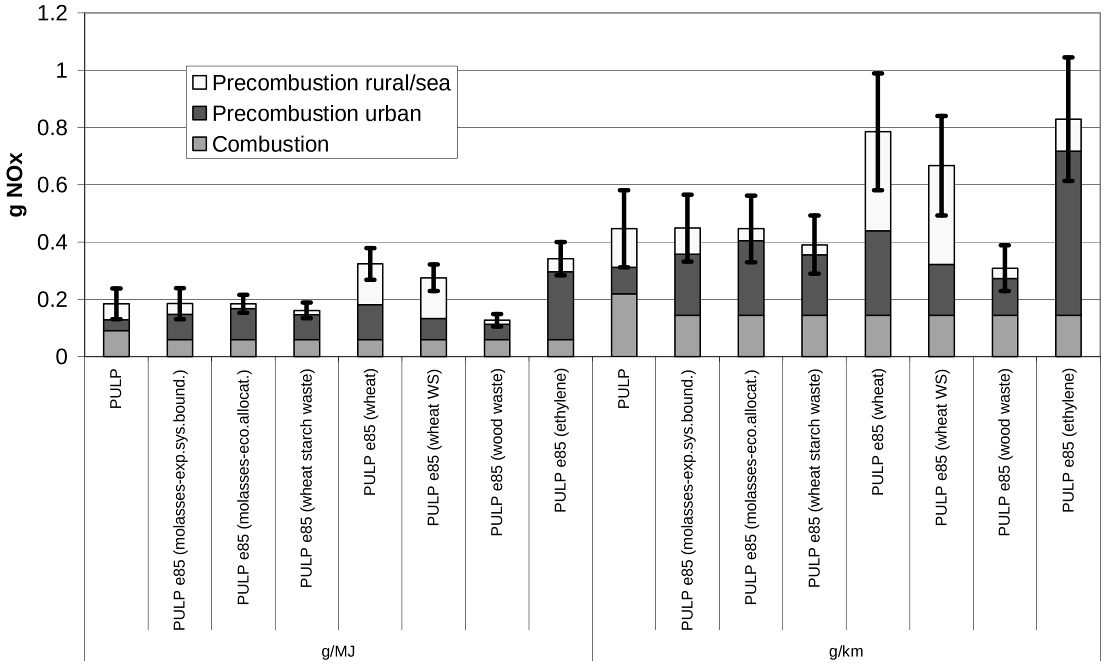

Figure 13.3
Exbodied emissions of oxides of nitrogen for premium unleaded petrol and anhydrous ethanol (E85P).

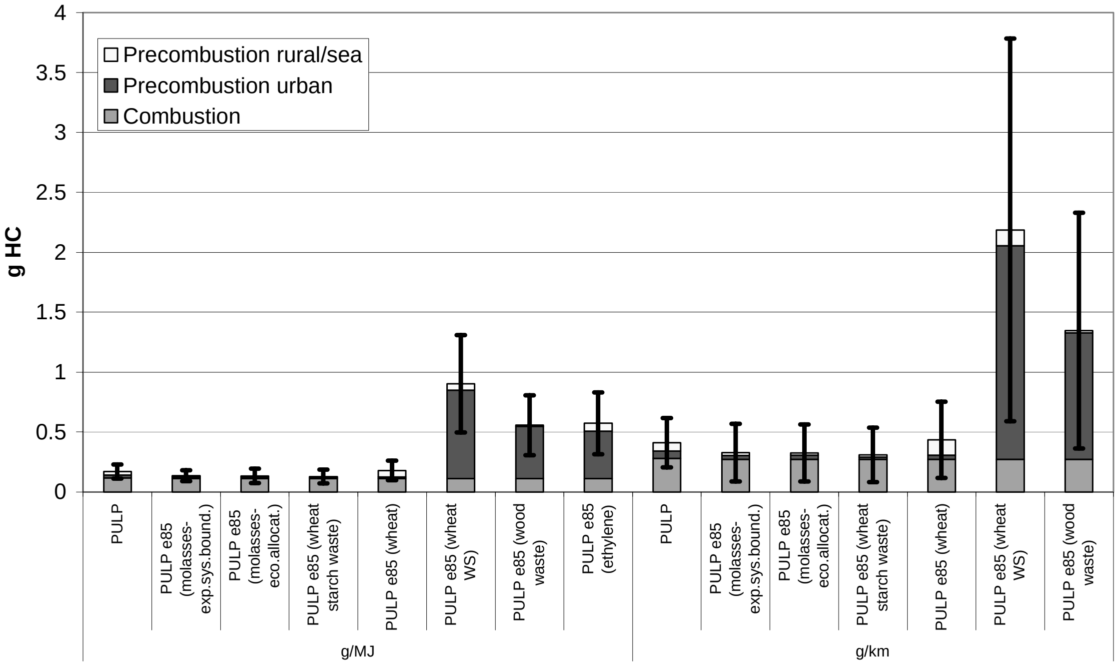

Figure 13.4
Exbodied emissions of hydrocarbons for premium unleaded petrol and anhydrous ethanol (E85P).

13.3 Viability and Functionality

There is considerable international experience on the use of ethanol in Brazil where sugar-derived ethanol is used as an automotive fuel. The ethanol used in Brazil is called Alcool and consists of 93% ethanol by volume. IEA Alternative Fuels Information Service (1996) note that “the techniques for the production and use of methanol and ethanol as a vehicle fuel are known. Obstacles that hinder the use of alcohols as a vehicular fuel are the relatively high costs of alcohol and the investments necessary to introduce an extra fuel.”

The viability and functionality issues related to ethanol and its use in heavy vehicles (as diesohol) or in light vehicles (as petrohol) have been examined in other chapters, and the same considerations will apply for E85P.

13.4 Health and OH&S

Ethanol produces a marked decline in the emissions of air toxics, except for the aldehydes. When weighting factors are applied, the weighted air toxics emissions from ethanol are below those of petrol.

13.5 Environmental Issues

ESD issues

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid. Provided that the source of ethanol is not fossil fuels then it satisfies ESD principles. The particulate emissions are lowered as are the emissions of ozone pre-cursors. The concentrations of emitted air toxics are lower from ethanol than from petrol.

In particular, we draw attention to the fact that appropriate disposal of the refinery waste-products is crucial to environmental impacts or benefits. Dunder application is often criticised as being the cause of poor waste quality in Queensland, though there is little evidence of this (www.sunfish.org.au/fishkills/fishkills.htm). Conversely, appropriate and careful disposal of dunder means that many farmers in the district near Sarina now use it as a fertiliser and soil conditioner - even though it was once considered a poison.

Sustainability
Ethanol from sugar or wheat is liable to be a niche fuel and thus there are no sustainability issues associated with it. Large-scale usage of ethanol will require ligno-cellulosic production to be economical.

Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia’s oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia’s croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large-scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

Groundwater
We are not aware of any issues related to groundwater contamination except to note that in the US the replacement of MTBE by ethanol in oxygenated fuels was specifically done to reduce groundwater contamination.

13.6 Expected Future Emissions

Ethanol can be expected to meet all future Australian Design Rules for all pollutants, except for hydrocarbon emissions.

13.7 Summary

13.7.1 Advantages

- As a renewable fuel it produces less fossil CO_2 than conventional fuels
- Tailpipe emissions of NOx and PM appear to be lower on average.
- Air toxic levels (except for aldehydes) are lower than those of conventional fuels.

13.7.2 Disadvantages

- Cold starting in cool climates is difficult unless ethanol is blended with petrol as a starting aid, or unless some other starting aid is used.

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14. Petrohol

14.1 Background

Anhydrous ethanol can be used as an additive in petrol. We use the term petrohol for a blend of 10% anhydrous ethanol in premium unleaded petrol. The symbols E10P or E10PULP are also used for this fuel, depending on whether it is necessary to specify the type of petrol (P) with which the ethanol is blended.

There has been substantial US interest in the use of ethanol in cars. The reason for this is that the Californian Government, through their Air Resources Board, requires vehicles to use “reformulated gasoline”. Originally such reformulated gasoline could be made by blending MTBE (methyl tertiary-butyl ether) into petrol. Because of the contamination of Californian groundwater with MTBE the Californian Governor ordered the removal of MTBE from petrol and studies on the environmental and health effects of ethanol in petrol. The use of ethanol produces an oxygenated fuel that satisfies the requirements of Californian reformulated gasoline.

Oygenates are added to petrol to improve the anti-knock performance and to reduce emissions. Reuter et al (1992) studied European petrol oxygenated with MTBE, ETBE and ethanol and found that the tailpipe emissions of oxygenated petrol are independent of the oxygenate that is used.

On 8 May 2001 the Minister for Environment and Heritage, Senator Hill, announced the first national fuel quality standard for petrol and diesel under the *Fuel Quality Standards Act 2000*. Senator Hill said in that context, that further assessments were necessary before setting an ethanol limit for petrol. Studies are currently being undertaken by independent experts and a decision is expected within 12 months.

14.2 Results

14.2.1 Greenhouse gas emissions

Figure 14.1 depicts the greenhouse gas emissions estimated for PULP, which we take as the reference fuel for light vehicles, as well as for petrohol. These are shown as emissions on an energy basis, and as emissions per kilometre for a car. The differences between exbodied greenhouse gas emissions of PULP and E10P are slight.

14.2.2 Particulate matter emissions

Figure 14.2 depicts the particulate matter (PM10) emissions estimated for PULP and E10P. These are shown as emissions on an energy basis, and as emissions on a per km basis for cars. Emissions of PULP and E10P are similar.

14.2.3 Emissions of oxides of nitrogen

Figure 14.3 depicts the oxides of nitrogen (NOx) emissions estimated for PULP and E10P. These are shown as emissions on an energy basis, and as emissions on a per km basis for cars. Emissions of PULP and E10P are similar.

14.2.4 Emissions of hydrocarbons

Figure 14.3 depicts the non-methanic hydrocarbon (HC) emissions estimated for PULP and E10P. These are shown as emissions on an energy basis, and as emissions on a per km basis for cars. Hydrocarbon emissions from E10P are generally similar to those from PULP.

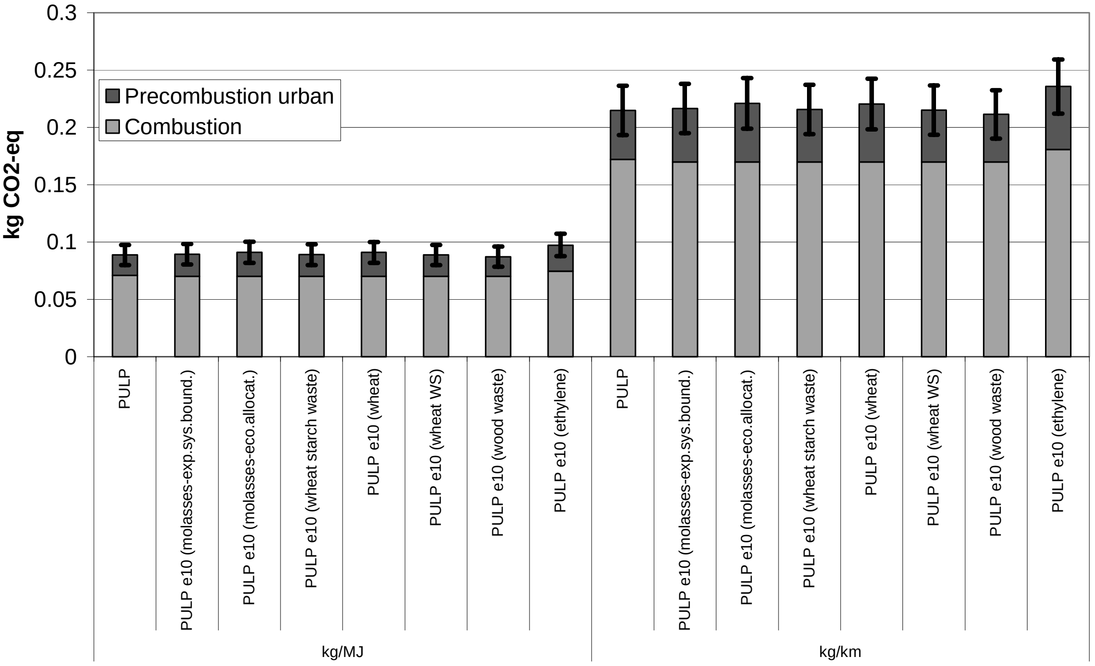

Figure 14.1
Exbodied emissions of greenhouse gases for premium unleaded petrol and petrohol.

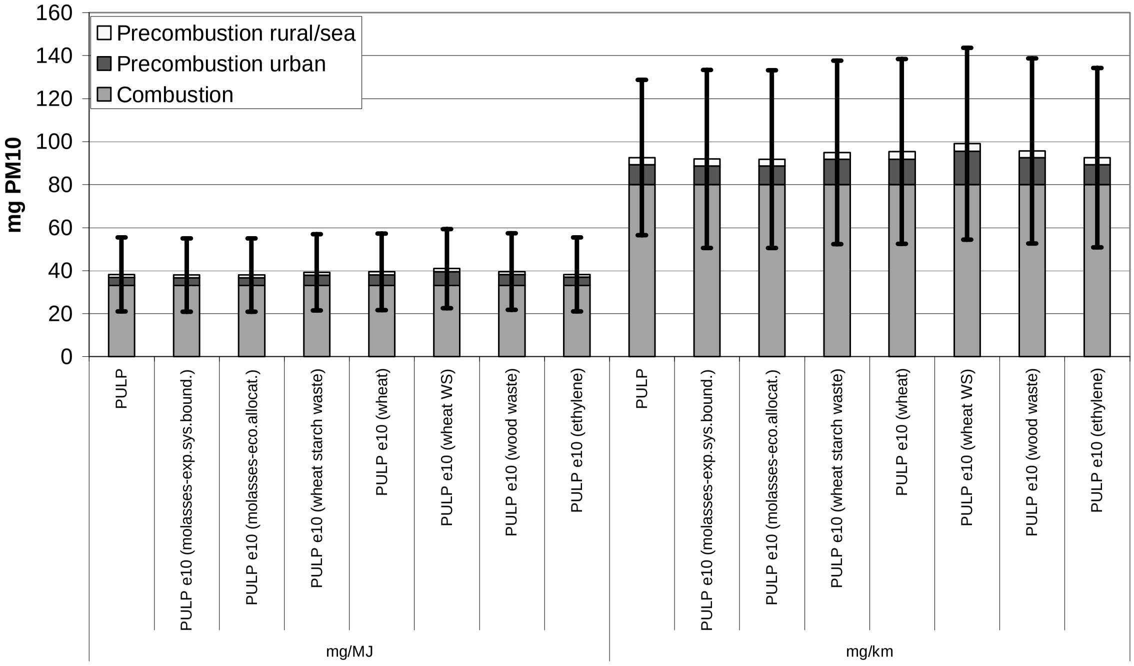

Figure 14.2
Exbodied emissions of particulate matter for premium unleaded petrol and petrohol.

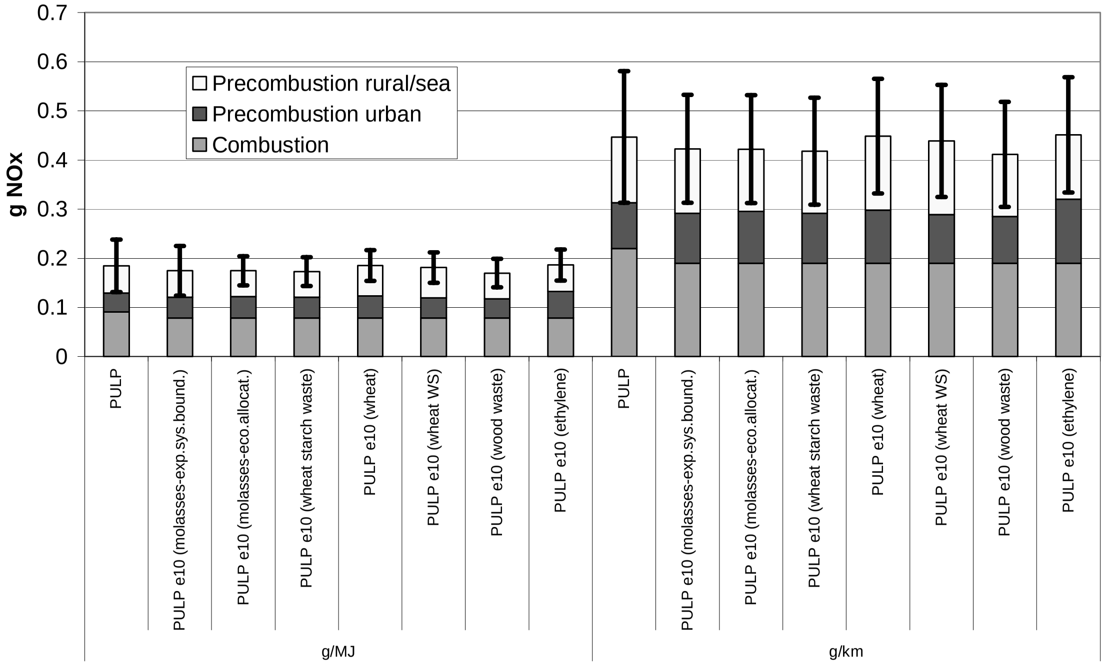

Figure 14.3
Exbodied emissions of oxides of nitrogen for premium unleaded petrol and petrohol.

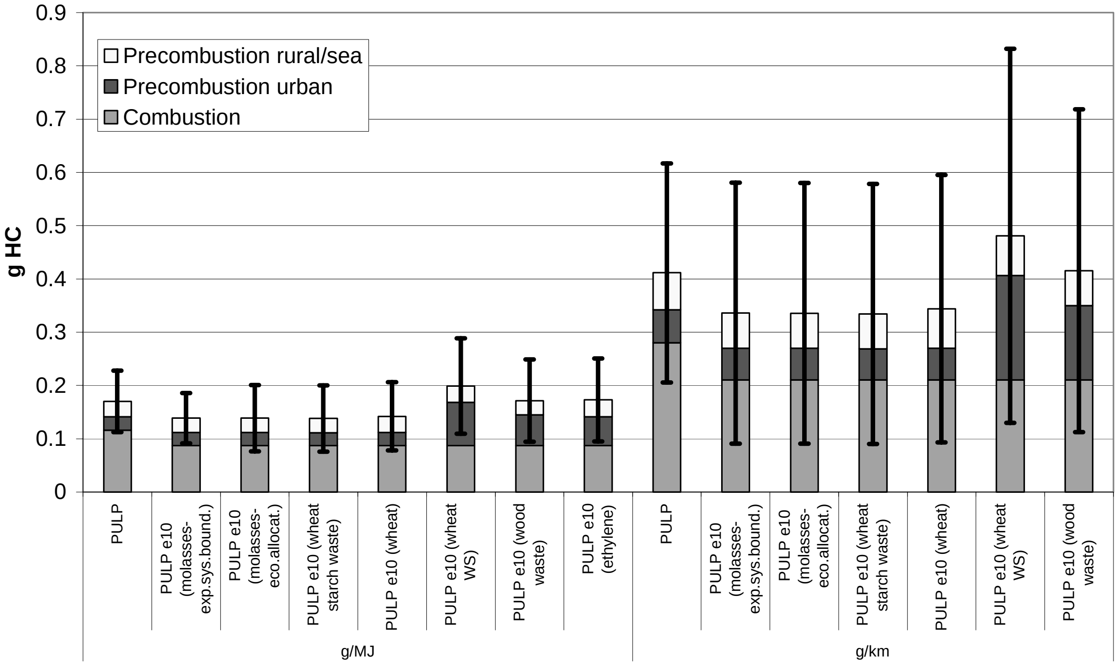

Figure 14.4
Exbodied emissions of hydrocarbons for premium unleaded petrol and petrohol.

14.3 Viability and Functionality

There is considerable international experience on the use of ethanol as a blend in petrol in the United States, where it is needed under the legislation requiring the use of reformulated gasoline, and in Brazil where sugar-derived ethanol is used as an automotive fuel and also as a blend (gasohol). No special engine modification or handling precautions are needed when using a 10% ethanol blend. Such widespread international experience indicates that the viability and functionality of petrohol will be much the same as of the corresponding petrol with which the ethanol is blended. Ethanol can loosen contaminants and residues that have been deposited by previous gasoline fills. These can collect in the fuel filter. This problem has happened occasionally in older cars, and can easily be corrected by changing fuel filters. Symptoms of a plugged fuel filter will be hesitation, missing, and a loss of power.

14.4 Health and OH&S

Motor vehicle emissions data indicates that the use of ethanol results in substantial reductions in air toxics emissions.

E10PULP tailpipe emissions of benzene, 1,3 butadiene, are substantially less than petrol vehicles, while formaldehyde emissions are similar. There is contradictory information about the emissions of acetaldehyde tailpipe emissions with some studies showing an increase while other show a decrease compared with petrol. More research is required to clarify this issue.

Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and a moderate irritant. The flash point of the fuel emulsion becomes that of alcohol when the alcohol content exceeds 5% of the volume.

Ethanol fuels increase permeation on elastomers that have been used in automotive applications (eg: rubber hoses, plastic fuels tanks). Research is required to quantify the permeation impacts of ethanol. (Harold Haskew & Associates, 2001)

14.5 Environmental Issues

ESD principles

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid. A blend of 10% ethanol with petrol will be more in accord with ESD principles than petrol on its own.

Sustainability

Ethanol from sugar or wheat is liable to be a niche fuel and thus there are no sustainability issues associated with it. Large-scale usage of ethanol will require ligno-cellulosic production to be economical, and the sustainability issues associated with such production have been discussed in the chapters on ethanol.

Ethanol is a renewable fuel. Petrol is a non-renewable fuel. A blend of 10% ethanol will be more sustainable than petrol on its own.

Groundwater contamination

There is no evidence of widespread groundwater contamination from petrohol, unlike fuels oxygenated with MTBE. It may be expected that petrohol has a similar impact on local groundwater supplies as petrol.

14.6 ADR Compliance

Petrohol can be expected to meet all future Australian Design Rules for all pollutants.

14.7 Summary

14.7.1 Advantages

- Tailpipe emissions of CO and HC appear to be lower on average.
- Air toxic levels decrease as the ethanol concentration increases.

14.7.2 Disadvantages

- There are high hydrocarbon evaporative emissions that require adjustment of the vapour pressure of the base petrol to which ethanol is added.
- There are problems of phase stability in the petrol mixture if water is present.

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15. Hydrogen

15.1 Introduction

The hydrogen energy content per unit mass is high. Compared to petrol for example, it is three times as high. On a volume basis, the energy content of hydrogen is relatively small. All mixtures of hydrogen and air with a volumetric hydrogen content between 4% and 75% are inflammable. Compared to mixtures of petrol and air, this is a wide range. Hydrogen can burn in mixtures with air from very lean (excessive air) to rich (excessive fuel).

15.2 Full Fuel Cycle Analysis Results

We consider only fuel-cell powered vehicles with the hydrogen derived from steam reforming of natural gas. Such hydrogen vehicles have virtually no emissions, even of NOx, because fuel cells operate at temperatures that are so much lower than internal combustion engines that NOx is not formed from the nitrogen and oxygen in the air. Theoretically, a hydrogen-fuelled fuel cell vehicle emits only water vapour.

15.2.1 Greenhouse gas emissions

Figure 15.1 depicts the greenhouse gas emissions estimated for the reference fuel (LSD) and hydrogen. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses. We have used data from Apelbaum Consulting Group (1997) for the passenger task and the freight task in Australia and taken the mean energy intensity for the Australian freight task to be 1.2 MJ/tonne-km (Apelbaum Consulting Group, 1997: p.118), and the energy intensity of buses to be 1.06 MJ/passenger-km (Apelbaum Consulting Group, 1997: p.116).

The upstream emissions of greenhouse gases from hydrogen manufacture equates closely to the total exbodied emissions of greenhouse gases from low sulfur diesel.

15.2.2 Particulate matter emissions

Figure 15.2 depicts the particulate matter (PM10) emissions estimated for hydrogen. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. In all cases but one the emissions of PM10 are less from hydrogen than from the reference fuel (LSD).

15.2.3 Emissions of oxides of nitrogen

Figure 15.3 depicts the oxides of nitrogen (NOx) emissions estimated for hydrogen. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. As a general rule the upstream NOx emissions from hydrogen processing are less than those of the reference fuel.

15.2.4 Emissions of hydrocarbons

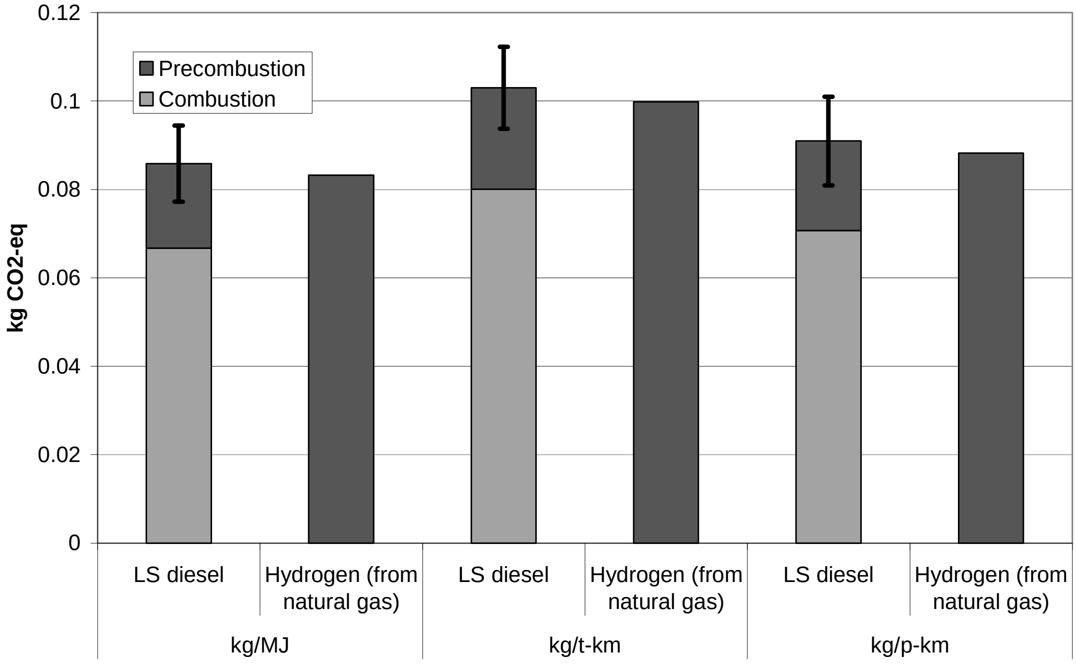

Figure 15.1
Exbodied emissions of greenhouse gases for low sulfur diesel and hydrogen

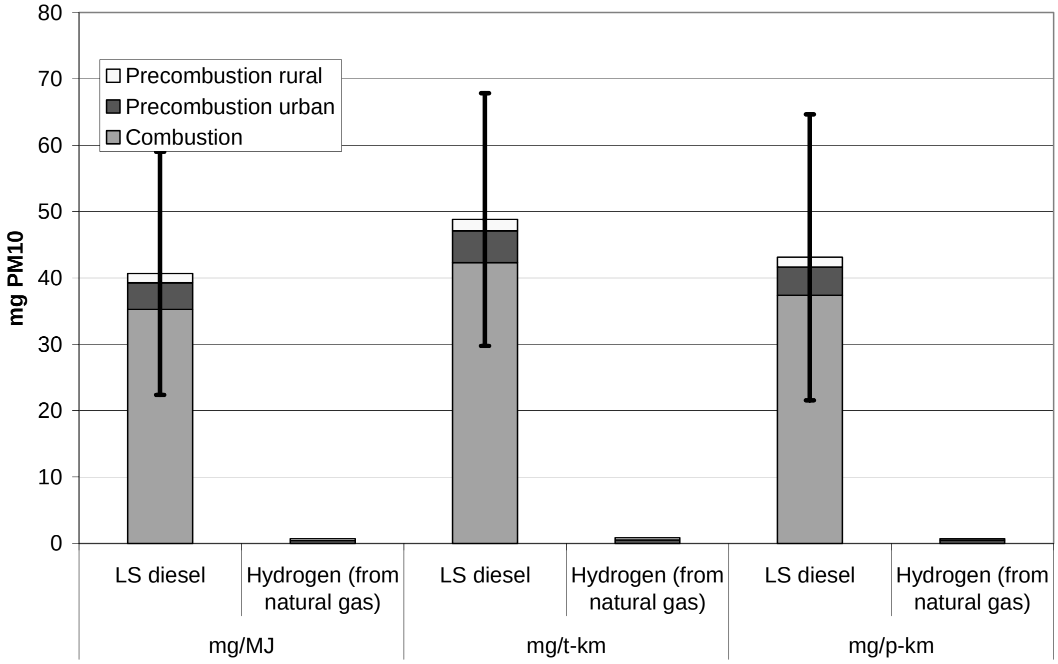

Figure 15.2
Exbodied emissions of particulate matter for low sulfur diesel and hydrogen

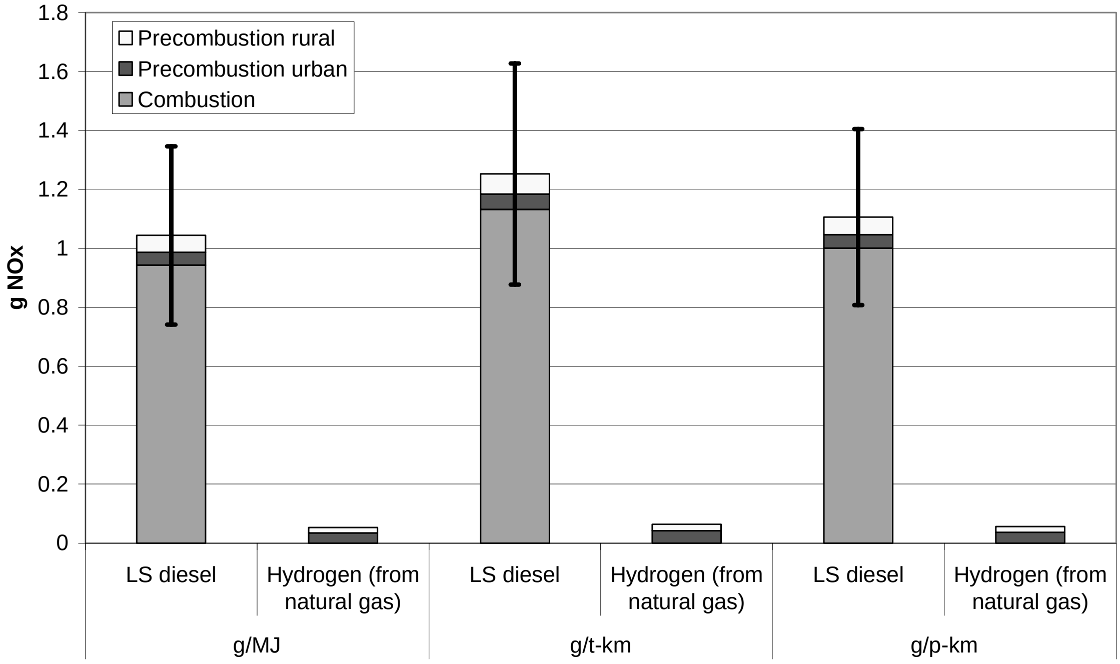

Figure 15.3
Exbodied emissions of oxides of nitrogen for low sulfur diesel and hydrogen

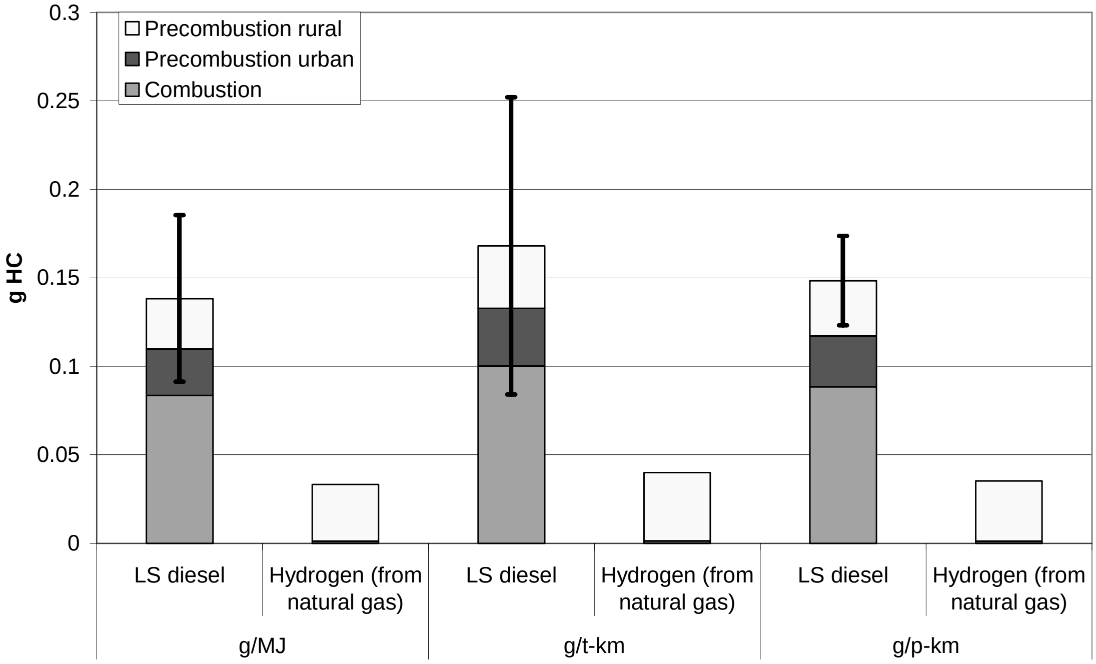

Figure 15.4
Exbodied emissions of hydrocarbons for low sulfur diesel and hydrogen

Figure 15.4 depicts the hydrocarbon (HC) emissions estimated for hydrogens. These are shown as emissions on an energy basis, as emissions on a per tonne-km basis for trucks, and on a per passenger-km basis for buses using the same energy intensities previously noted. Hydrogen has very low emissions of hydrocarbons compared to diesel.

15.3 Viability and Functionality

Important advantages of fuel cells are: high energy efficiency, because the efficiency is not limited to the maximum efficiency of thermal energy processes; low emissions during operation, though manufacturing of fuel cells may cause emissions as shown in Figures 15.1 to 15.4; and low noise production. However, fuel cells have some disadvantages as well. Compared to internal combustion engines, the disadvantages are: fuel cells are very expensive; and fuel cells are large and heavy per kW output.

Hydrogen rises when it is released into the open air. Its safety is then similar to that of conventional fuels. To avoid explosions, evaporating hydrogen is extracted during the refuelling process. The safety of hydrogen fuel systems is important during vehicle collisions. There is substantial testing designed to ensure leakproof hydride tanks, and to place the vehicle tank inside the safety cage of vehicles so as to reduce the risk of damage to the tank during a collision. No results from collision tests with hydrogen vehicles could be found in the literature.

The refuelling time of a hydrogen vehicle can be up to ten times the refuelling time of a petrol vehicle.

15.4 Health Issues

There are no air pollutant or greenhouse gas emissions during operation. The only emissions that may be of concern arise during precombustion.

Hydrogen upstream emissions of both particulate matter and HC are substantially less than LSD. Hydrogen has no tailpipe emissions of particulate matter or air toxics.

15.5 Environmental Impact and Benefits

ESD issues

It is difficult to see how natural gas reforming to produce hydrogen could be seen as ecologically sustainable development. It uses a fossil fuel, and considerable energy (and thus exbodied greenhouse gases), to manufacture the fuel. Production of hydrogen by low pressure water electrolysis would be an ecologically sustainable method of production, provided the electricity to undertake the electrolysis is based on renewable energy.

Sustainability

Present plans are for hydrogen to be generated from steam reforming of natural gas in the Northwest Shelf. Though there are large amounts of natural gas available, this uses a fossil fuel to produce hydrogen. An innovative, sustainable scheme has been proposed based on using tidal power to dissociate hydrogen and thus run a hydrogen economy. The theoretical potential is there for great environmental benefits provided the technology can be implemented.

Groundwater contamination

Hydrogen is a gaseous fuel with no air pollutant or greenhouse gas emissions. It thus cannot contaminate soil or water.

1. Low Sulfur Diesel

1.1 Diesel National Environment Protection Measures

With the establishment of the National Environment Protection Council, as a result of the May 1992 Intergovernmental Agreement on the Environment, Australia decided to declare National Environment Protection Measures (NEPMs) so as to enact uniform national environmental standards. Information on NEPMs may be found at the National Environment Protection Council website at www.nepc.gov.au. The NEPMs that relate, either directly or indirectly, to motor vehicles and their emissions are the NEPM for Ambient Air Quality, the National Pollutant Inventory (NPI), the Diesel Vehicle Emissions NEPM, and the proposed Air Toxics NEPM. The NEPM for Ambient Air Quality sets air quality standards for the ambient environment, and does not deal with emissions, as such. Emission controls on new vehicles are achieved through Australian Design Rules (ADRs). The NPI requires industry to report on emissions.

1.1.1 Diesel vehicle emissions

The emissions of most interest in relation to diesel vehicles are oxides of nitrogen (NOx), hydrocarbons, and fine particles (also known as fine particulates, which is an incorrect elision of fine particulate matter). NOx are a precursor to the formation of photochemical smog. There is also evidence that NOx reacts with other pollutants to form particles. Fine particles have been identified as a major health risk. The smaller the particle, the greater the risk.

Motor vehicles, particularly those with diesel engines, are significantly disproportionate contributors of fine particle pollution and oxides of nitrogen in urban areas. Since 1996 diesel vehicle emission standards in the ADRs (http://www.dot.gov.au/land/environment/envrev99.htm) have placed limits on the emission of particles for new vehicles. Before 1996, diesel vehicles sold in Australia were required to meet a smoke opacity standard. Amendments to Australian ADRs for diesel vehicle emissions, gazetted in 1999, will bring about the introduction of Euro2, Euro3 and Euro4 standards from 2002.. These standards are described in more detail in section 1.3, below.

1.2 Diesel Fuel and the Diesel Engine

1.2.1 Introduction

Most heavy vehicles over 10 tonnes gross vehicle mass (GVM) use turbocharged, four-stroke compression ignition engines. Smaller vehicles use normally aspirated engines. All are commonly referred to as ‘diesel engines’. Fuel is injected into the diesel engine at over 1000 atmospheres pressure and ignited by the heat of compression, whereas in the petrol engine the fuel is ignited by a spark from a spark plug.

1.2.2 Fuel quality review

In 1999, Environment Australia commissioned a comprehensive review of possible new fuel specifications for Australia, designed to reduce emissions of greenhouse gases and air pollutants from Australian road transport. In addition to modelling emissions reductions, the project assessed the impact on Australian refineries, vehicle manufacturers, consumers and the economy-wide effects of changing fuel specifications for petrol and diesel. The reports (Environment Australia, 2000a, 2000b) of the fuel quality review are available at http://www.ea.gov.au/atmosphere/transport/fuel/index.html .

Low sulfur diesel (LSD) is diesel fuel that meets either the Euro2 fuel specifications for diesel fuel, or the fuel specifications for LSD proposed by the Commonwealth for implementation in 2002.

Table 1.1
Diesel fuel quality specifications (Environment Australia, 2000a, 2000b)

Fuel parameter	Euro2 (EN590:1993)	Commonwealth (1 January 2002)[1]
Sulfur (ppm)	500	500
Cetane index	46 (min)	46 (min)
Density at 15°C (kg/m^3)	820 – 860	820 – 860
Distillation T95 (°C)	370 (max)	370 (max)
Ash & suspended solids (ppm)	-	100 (max)
Viscosity (cSt)	-	2.0 – 4.5

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. LSD is produced in refineries with a hydro-desulfurisation unit. As at March 2001, Western Australia and Queensland had passed legislation mandating a diesel sulfur content of 500 ppm or less.

1.2.3 Emission factors

A CO_2 emission factor of 69.7 g/MJ for diesel fuel (of energy density 38.6 MJ/L) may be found in Workbook 3.1 on transport of the Australian Greenhouse Gas Inventory methodology (National Greenhouse Gas Inventory Committee, 1998), whereas, for other emissions, the default emission factors are as given in Table 1.2.

Table 1.2
Emission factors for diesel vehicles expressed as g/km

Vehicle	CH_4	N_2O	NOx	CO	NMVOC
Light trucks	0.01	0.014	1.18	1.11	0.53
Medium trucks	0.02	0.017	3.1	1.82	0.99
Heavy trucks	0.07	0.025	15.29	7.86	3.78
Buses	0.03	0.025	4.9	2.88	1.56

Source: National Greenhouse Gas Inventory Committee (1998)

1.3 Upstream and Tailpipe Emissions

1.3.1 Upstream

Diesel fuel is manufactured using crude oil as a feedstock. Depending on the characteristics of the crude oil(s) used, a number of different refinery streams may be blended to produce diesel fuel complying with the relevant specification. These streams most commonly include straight run distillate and light cycle oil (LCO) produced from heavier fractions in a fluid catalytic cracker. The sulfur content of these fractions depends on the feedstock crude oil used and may be as high as 2%; their boiling range falls between 150°C and 380°C.

Diesel fuel currently used in Australia has a sulfur content of around 1300 ppm. As from 31 December 2002, new LSD specification will apply, requiring sulfur content of diesel fuel to be 500 ppm or lower.

High levels of sulfur in diesel fuel are undesirable, as during combustion they are converted to volatile sulfur oxides (SOx). These are corrosive and lead to increased engine wear. They also contribute directly to acid rain and produce solid sulfates, which add to the particulate matter in the exhaust gases.

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[1] The sulfur specification takes effect 31 December 2002.

Hydro-desulfurisation is the process that is most commonly used to reduce sulfur in fuel. The process involves catalytic hydrogenation, which converts chemically bound organic sulfur into hydrogen sulfide (H_2S). It also improves the cetane number.

To meet the 500 ppm limit, a single-stage hydro-desulfurisation unit using a Cobalt-Molybdenum (Co-Mo) catalyst, and sometimes Nickel-Molybdenum (Ni-Mo) catalyst, under moderate severity, is adequate. Further sulfur removal — down to <15 ppm in the case of ultra-low sulfur diesel (ULSD) — requires a two-stage, high severity hydro-desulfurisation unit using both the Co-Mo and Ni-Mo catalysts.

Energy use for oil and gas production and transportation, and refinery processing, is taken from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000) and shown in Table 1.3. This excludes exploration activity.

Note that oil and gas are assumed to be produced together and emissions and extraction energy are allocated between them based on the energy content of each fuel. Similarly, refinery products, such as diesel, petrol, LPG and so on, are treated as co-products with the energy consumption, and consequent emissions being allocated to the output products (diesel, petrol, LPG), based on the energy content of each fuel.

In addition to the energy use detailed in table 1.3, energy and emissions for transportation of crude oil imported into Australia are taken into account. Assumptions for oil imports are also taken from the National Greenhouse Gas Inventory, with 58% of crude taken to be transported 10,000 km predominantly from Malaysia and the Middle East.

Table 1.3
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use	Production 1998[3]	Energy Use to production energy ratio
		PJ	PJ	GJ/PJ produced
Oil and gas production and field processing	Petroleum	0.9[1]	2528.6	0.36
	Gas	141.1[1]	2528.6	55.80
Natural gas transmission	Gas	8.6[1]	688.5	12.49
Gas production and distribution	Gas	2.4[1]	371.5	6.46
Petroleum Refining	Petroleum	87.2[2]	1663.8	52.41
	Gas	11.6[2]	1663.8	6.97

[1] Fuel Combustion Activities 1A-2 (sheet 1): Emissions from manufacturing industries and construction (all sources) (NGGIC)
[2] Fuel Combustion Activities 1A-1 (sheet 2): Emissions from Energy Industries (all sources) (NGGIC)
[3] Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas (NGGIC)

Emissions from combusted fuels and fugitive emissions are also taken from the National Greenhouse Gas Inventory and are shown in Table 1.4.

No Australian aqueous emissions or solid wastes data was available for the crude oil, natural gas production or transport sectors, so data from European studies (Boustead, 1993) was used as a proxy. This data is detailed in Table 1.5 and Table 1.6.

Table 1.4
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO_2	CH_4	N_2O	NOx	CO	NMVOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	1257	14.8	0.2				0.1
	Crude oil production	298		0.3				0.3
	Crude oil transport: domestic	1664		0.2				1.3
	Crude oil refining and storage	1102	153	1.9		0.1	0.5	34
	Petroleum product distribution							57.9
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for oil and gas production	Venting at gas processing plant	1272	2814	119.6				42.3
	Distributed venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

Table 1.5
Aqueous emissions for Oil and Natural Gas Production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Acid as H+	1.56	0.53
metallic ions	0.19	0.09
CxHy	0.19	0.09
suspended solids	1.56	0.71
dissolved solids	1.36	0.18
dissolved organics	0.78	0.36
oil	1.36	0.53
phenol	0.02	0.02

Source: Boustead (1993)

Table 1.6
Aqueous emissions for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
industrial waste	0.78	0.71
mineral waste	0.08	0.07
slags/ash	11.70	10.67
inert chemicals	0.39	0.36

Source: Boustead (1993)

For refineries, data on trace metals and volatile organic fugitive emissions was taken from the National Pollutant Inventory Guide book (Environment Australia, 1999b), together with data submitted by refineries to the National Pollutant Inventory.

The controlled emission factor for particle emissions from Fluid Catalytic Cracking Units is taken as 0.128 kg/m^3 feed to the unit (page 19, Table 10 (Environment Australia, 1999b). From this data, trace metal emission data is estimated using emission factors provided in the NPI guidebook (Environment Australia, 1999b: Table 11, p.20), which are shown in Table 1.7.

Table 1.7
Metal emissions to air for particulate matter from refinery operations

Metal emission	Controlled emission factor as weight % of total particulate matter
Nickel	0.031
Copper	0.003
Zinc	0.006
Selenium	0.003
Antimony	0.002
Lead	0.01
Cadmium	0.002
Mercury	0.001

Source: Extracted from Environment Australia (1999b: Table 11 page 20)

Volatile organic emissions were estimated using emission factors related to total volatile organic compound (VOC) emissions from fugitive emissions in refineries, given in the NPI guidebook (Environment Australia, 1999b: Table 15 p. 31). Data was given for a range of fugitive leaks such as flanges, valves, drains and pump seals. The lowest and most common was the data for flanges and valves, so this data was used to breakdown the VOC emissions reported in the National Greenhouse Gas Inventory into different organic species as shown in Table 1.8.

Table 1.8
Speciation data for NPI Substances from Equipment Fugitives[1]

Compound	Compound Weight Percent in VOCs Released
n-hexane	4.76
Cyclohexane	0.14
Xylenes	0.28
Benzene	0.14
Toluene	0.7

Source: Extracted from Environment Australia (1999b: Table 15 page 32)
[1] Emission factors are for flange and valves

Organic and trace metal emissions to water were also determined from data in the NPI Guide. Metal emissions are provided per cubic metre of waste water (Environment Australia, 1999b: Table 20 p. 41), while organic emissions are provided as a weight percent of dissolved organic carbon (Environment Australia, 1999b: Table 19 p. 40. Waste water effluents and DOC loads per tonne of production was estimated from reported emission data from refineries to the National Pollutant Inventory. The data was conservatively estimated by dividing total flow by capacity, rather than production. This would reduce the result on a per tonne basis. Emission factors for organics to water are presented in Table 1.9, while factors for metals emitted are provided in Table 1.10. The calculated average wastewater emission for Australian refineries was 30 L per tonne of product and dissolved organic carbon (DOC) was calculated to be around 0.79 g per tonne of product.

Table 1.9
Default Speciation Factors for Organics in Refinery Effluent

Organic substance	NPI Substance Weight Percent of DOC
Toluene	0.00092
Benzene	0.00091
Xylenes	0.00140
Phenol	0.00069
1,2-Dichloroethane	0.00027
Hexachlorobenzene	0.00000
Polycyclic aromatic hydrocarbons	0.00160
Styrene	0.00010
Ethylbenzene	0.00012
1,1,2-trichloroethane	0.00004
Chloroform	0.00250

Source: Environment Australia (1999b: Table 19 p. 40)

Figure 1.1 provides an overview of how the unit processes are put together in the LCA inventory, with flows from each process shown for 1 kg of diesel production.

Table 1.10
Default Emission Factors for Trace Elements and Inorganics in Refinery Effluent

Trace Elements	NPI Substance Emission Factors (kg/m^3 of flow)
Zinc	4.40E-04
Phosphorous	4.10E-07
Arsenic	6.70E-06
Chromium(VI)	7.70E-06
Selenium	3.10E-06
Nickel	3.60E-06
Copper	2.90E-06
Antimony	5.80E-07
Cobalt	1.60E-06
Mercury	1.10E-08
Cadmium	3.30E-07
Lead	1.90E-06
Cyanide	7.60E-09
Ammonia	1.30E-06

All energy use throughout fuel processing is assumed to have a greenhouse emission profile as of standard fuel combustion, as described in the National Greenhouse Gas Inventory in Fuel Combustion Activities 1A-1 (sheet 1): Emissions from Energy Industries (all sources) (NGGIC, 1998). Air emissions of organic and inorganic substances, and particles, are taken from the National Pollutant Inventory Emission Estimation Technique Manual for Combustion in Boilers (Environment Australia, 1999a). Grid-supplied electricity data were taken from the Australian LCA inventory data project, described in (Grant, 2000).

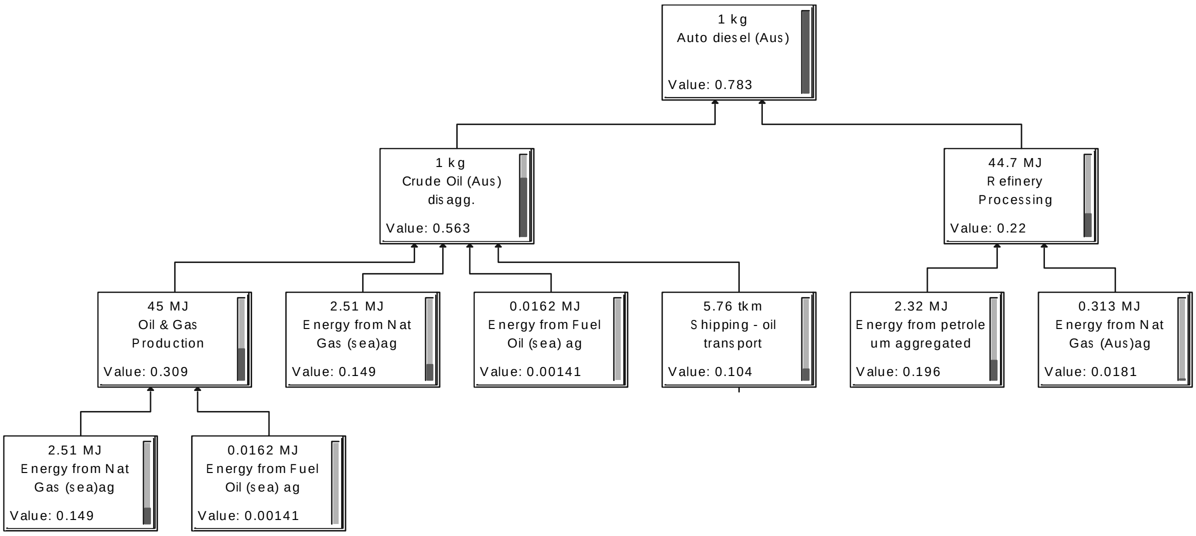

Figure 1.1
Processes leading into diesel production as modelled in LCA software.
(The diagram shows the energy flows per kilogram of LSD. The lower value in each box is set to display cumulative greenhouse gas emissions in kg CO_2-eq.)

Assumptions for Production of LSD

Discussions with Mr Mark Sanders of BP, an expert in refinery operation, updated the previous assumptions that were made regarding additional processing to produce lower sulfur diesel. For LSD (500 ppm S) a hydro-desulfurisation unit would be required on top of current refinery operations. Beer et al. (2000) assumed that for ULSD a hydro-cracking unit would be required on top of normal refinery operations. More recent information indicates that existing hydrofiners can be used to produce ULSD by employing more active catalysts, increased hydrogen purity, and reduced space velocities. In the absence of better data, information on the two processes has been taken from standard equipment specifications. The data for this is shown in Table 1.11.

Table 1.11
Additional inputs to produce 1 tonne LSD and ULSD from 1 tonne current diesel

	Equipment	Electricity	Energy from gas oil	Steam
		kWh	MJ	kg
Low sulfur	Hydro-desulfurisation unit	7.3	577	0
Ultra low sulfur	Hydro-cracking unit	50.3	1578	95

Source: J. Hydrocarbon Processing as supplied by M. Sanders (pers comm. 8 Feb. 2000)

1.3.2 Tailpipe emissions

There have been two major investigations conducted in Australia of the tailpipe emissions from LSD. Brown et al. (1999) used a four-mode steady-state chassis dynamometer based test derived from the SAE 13-mode test to examine four vehicles — a medium-duty truck with Euro1 engine technology (1992 Ford Trader of 7,075 kg gross vehicle mass), a Euro1 engine technology bus (1987 Mercedes Mark 4 of 16,000 kg GVM), a Euro2 technology bus (1996 Scania 11L Turbo of 19,100 kg GVM), and a Euro1 engine technology heavy duty truck (1991 Volvo NL12 Heavy Tipper of 25,000 kg GVM). The vehicles were examined using diesel fuel, with (D+C) and without (D) a fitted catalytic converter, and using LSD fuel, with (LSD+C) and without (LSD) a fitted catalytic converter. The catalytic converters were oxidation catalysts on metallic or ceramic substrates. The emission results for the main pollutants are given in Table 1.12 to Table 1.15.

Table 1.12
Tailpipe emissions of CO (g/kWh) for various types of diesel

	MD	Bus	Euro2	HD
	Ford Trader	Mercedes Mk4	Bus Scania	Truck Volvo
D	5.96	7.11	0.54	2.68
LSD	5.97	7.95		2.39
D+C	0.63	3.56	0.2	1.51
LSD+C	0.57	3.31	0.1	0.95

Source: Brown et al. (1999)

Table 1.13
Tailpipe emissions of NOx (g/kWh) for various types of diesel

	MD	Bus	Euro2	HD
	Ford Trader	Mercedes Mk4	Bus Scania	Truck Volvo
D	8.23	14.1	9.2	9.77
LSD	8.76	13.9		10.5
D+C	7.89	11.9	8.84	10.6
LSD+C	7.41	12.5	9.02	11

Source: Brown et al. (1999)

Table 1.14
Tailpipe emissions of THC (g/kWh) for various types of diesel

	MD	**Bus**	**Euro2**	**HD**
	Ford Trader	**Mercedes Mk4**	**Bus Scania**	**Truck Volvo**
D	1.45	1.7	0.42	0.4
LSD	1.62	1.84		0.39
D+C	0.21	1.14	0.2	0.24
LSD+C	0.15	1.12	0.09	0.22

Source: Brown et al. (1999)

Table 1.15
Tailpipe emissions of PM (at rated speed, 75% power) (mg/kWh) for various types of diesel

	MD	**Bus**	**Euro2**	**HD**
	Ford Trader	**Mercedes Mk4**	**Bus Scania**	**Truck Volvo**
D	194	133	19	92
LSD	221	155		127
D+C	366	193	27	138
LSD+C	451	167	43	104

Source: Brown et al. (1999)

Parsons Australia Pty Ltd (2000) examined the emissions from two vehicles using the Australian Composite Urban Emissions Drive Cycle (CUEDC, pronounced Q-DC). Their results, using six different diesel fuels of varying sulfur content, are given in Table 1.16 and Table 1.17. The values in Table 1.17 have been used to determine tailpipe emissions in Table 1.23.

Table 1.16
Emissions from a Euro 1 technology (ADR70) Light Commercial Vehicle (1993 Toyota Hilux) using a range of diesel fuels.

	S content mg/kg	CO_2 g/km	CO g/km	NOx g/km	HC g/km	PM (filter) mg/km	FC L/100 km
Base Fuel	1700	464	3.16	1.62	0.04	741	18.21
Euro2	480	444	1.15	1.47	0.02	353	18.22
Euro3	210	435	0.74	1.49	0.04	293	17.53
Euro4	39	439	1.24	1.48	0.04	331	17.86
WorldWide	24	452	1.29	1.42	0.05	301	18.52
CARB	264	439	1.69	1.28	0.04	419	17.68

Source: Parsons Australia Pty Ltd (2000: Table 5.3)

Table 1.17
Emissions from a Euro 1 technology (ADR70) Rigid Truck (1995 Isuzu 900SUR) using a range of diesel fuels.

	S content Mg/kg	CO_2 g/km	CO g/km	NOx g/km	HC g/km	PM (filter) mg/km	FC L/100 km
Base Fuel	1700	782	3.45	10.63	1.01	447	32.92
Euro2	480	719	2.48	10.17	0.9	380	30.18
Euro3	210	746	2.75	10.47	0.95	313	31.22
Euro4	39	718	3.13	8.66	0.73	284	30.53
WorldWide	24	692	2.81	8.4	0.73	283	29.6
CARB	264	775	2.63	8.57	0.84	300	31.56

Source: Parsons Australia Pty Ltd (2000: Table 5.4)

1.4 Full Fuel-Cycle Analysis of LSD Emissions

Coffey (2000) conducted modelling studies to estimate life-cycle emissions as a result of improved fuel quality, tighter emission controls on petrol and diesel vehicles, and a lower growth in transportation as the Kyoto Protocol commitments are met. The results may be found at: http://www.ea.gov.au/atmosphere/transport/fuel/index.html .

Diesel vehicles reduce their emissions of sulfur dioxide when using low and ultra-low sulfur fuels. The increased processing at the refinery indicates that the life-cycle greenhouse gas emissions are liable to increase. There are strong theoretical arguments to indicate that reducing fuel sulfur, *per se*, will not alter the fuel economy of an engine. Nevertheless, the recent fuel economy results of Parsons Australia Pty Ltd (2000) confirm that there is an approximate 10% increase in fuel efficiency when LSD is substituted for diesel as in Table 1.17.. This confirms the results obtained on London buses that were noted in Table 2.1 of Beer et al. (2000). Desulfurisation produces changes to fuel properties such as the cetane value.. It is likely that the fuel economy will vary among LSDs from different sources.

The pre-combustion estimates for LSD were based on the assumption that existing Australian refineries will need to install a hydro-desulfurisation unit to produce LSD. The Stage 1 report (Beer et al. 2000) assumed that a hydro-cracker was needed to produce ULSD. Recent analyses (M. Sanders, pers. comm.) indicate that Australian refineries may be able to produce

ULSD using hydro-desulfurisation units by modifications as described earlier, or for new units by increasing the operating pressures.

1.4.1 Emissions on a mass per unit energy basis

The results obtained by using the SimaPro life-cycle model along with the upstream and tailpipe emissions data is given in Table 1.18 for the full life cycle for greenhouse gases and criteria pollutants. The upstream emissions and the tailpipe emissions that comprise these totals are given in Table 1.19 and Table 1.20, respectively. They have also been used to represent bus emissions by using the Leung and Williams (2000) model to represent emissions from a bus generating the same tractive force as the truck.

Table 1.18
Urban and total life-cycle emissions calculated for LSD

Full Lifecycle	Units (per MJ)	LS Diesel engine
Greenhouse	kg CO_2	0.0858
NMHC total	g HC	0.140
NMHC urban	g HC	0.111
NOx total	g NOx	1.044
NOx urban	g NOx	0.987
CO total	g CO	0.253
CO urban	g CO	0.242
PM10 total	mg PM10	40.7
PM10 urban	mg PM10	39.3
Energy Embodied	MJ LHV	1.18

The results separate urban and rural emissions, rural being the difference between total emissions and urban emissions. Emissions were assumed to occur in urban areas unless they were produced by a known rural or maritime activity.

The apparent discrepancies in certain values, when compared with tabulations earlier in this report, arise because many of the values reported in the main text are in terms of g/MJ measured as useable energy from the engine driveshaft (normally represented as g/kWh), whereas the life-cycle calculations are consistent in setting all the calculations in terms of g/MJ, based on the inherent chemical energy of the fuel. On average, this reduces quoted engine dynamometer values by a factor of 3.

Table 1.19
Urban and total upstream emissions (per MJ) for LSD

Precombustion	Units	LSD
Greenhouse	kg CO_2	0.0191
NMHC total	g HC	0.0565
NMHC urban	g HC	0.027
NOx total	g NOx	0.100
NOx urban	g NOx	0.043
CO total	g CO	0.023
CO urban	g CO	0.012
PM10 total	mg PM10	5.42
PM10 urban	mg PM10	4
Energy Embodied	MJ LHV	1.18

Table 1.20
Urban and total tailpipe emissions (per MJ) from LSD

Combustion	Units	LSD
Greenhouse	kg CO_2	0.067
NMHC total	g HC	0.084
NMHC urban	g HC	0.084
NOx total	g NOx	0.944
NOx urban	g NOx	0.944
CO total	g CO	0.230
CO urban	g CO	0.230
PM10 total	mg PM10	35.26
PM10 urban	mg PM10	35.26
Energy Embodied	MJ LHV	0

1.4.2 *Vehicle emissions - trucks (g/km)*

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 1.21
Urban and total life-cycle emissions (per km) for trucks calculated for LSD

Full LC	Units	LSD
Greenhouse	kg CO_2	0.9250
NMHC total	g HC	1.509
NMHC urban	g HC	1.192
NOx total	g NOx	11.250
NOx urban	g NOx	10.638
CO total	g CO	2.723
CO urban	g CO	2.612
PM10 total	mg PM10	438.4
PM10 urban	mg PM10	423.1
Energy Embodied	MJ LHV	12.70

Table 1.22
Urban and total precombustion emissions (per km) for trucks calculated for LSD

Precombustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.2060
NMHC total	g HC	0.609
NMHC urban	g HC	0.292
NOx total	g NOx	1.080
NOx urban	g NOx	0.468
CO total	g CO	0.243
CO urban	g CO	0.132
PM10 total	mg PM10	58.4
PM10 urban	mg PM10	43.1
Energy Embodied	MJ LHV	12.7

Table 1.23
Urban and total tailpipe emissions (per km) for trucks calculated for LSD

Combustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.719
NMHC total	g HC	0.900
NMHC urban	g HC	0.900
NOx total	g NOx	10.170
NOx urban	g NOx	10.170
CO total	g CO	2.480
CO urban	g CO	2.480
PM10 total	mg PM10	380.00
PM10 urban	mg PM10	380.00
Energy Embodied	MJ LHV	0

1.4.3 *Vehicle emissions - buses (g/km)*

This section gives the calculated values for the emissions from buses, on a per-kilometre basis.

Table 1.24
Urban and total life cycle emissions (per km) for buses calculated for LSD

Full LC	Units	LSD
Greenhouse	kg CO_2	1.66
NMHC total	g HC	2.71
NMHC urban	g HC	2.14
NOx total	g NOx	20.20
NOx urban	g NOx	19.10
CO total	g CO	4.89
CO urban	g CO	4.69
PM10 total	mg PM10	787
PM10 urban	mg PM10	760
Energy Embodied	MJ LHV	22.8

Table 1.25
Urban and total precombustion emissions (per km) for buses calculated for LSD

Precombustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.37
NMHC total	g HC	1.09
NMHC urban	g HC	0.52
NOx total	g NOx	1.94
NOx urban	g NOx	0.84
CO total	g CO	0.44
CO urban	g CO	0.24
PM10 total	mg PM10	104.9
PM10 urban	mg PM10	77.4
Energy Embodied	MJ LHV	22.8

Table 1.26
Urban and total tailpipe emissions (per km) for buses calculated for LSD

Combustion	Units	LSD (Aus)
Greenhouse	kg CO_2	1.2910
NMHC total	g HC	1.616
NMHC urban	g HC	1.616
NOx total	g NOx	18.270
NOx urban	g NOx	18.270
CO total	g CO	4.453
CO urban	g CO	4.453
PM10 total	mg PM10	682.3
PM10 urban	mg PM10	682.3
Energy Embodied	MJ LHV	0.00

1.4.4 *Uncertainties*

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 1.27.

Table 1.27
Estimated one standard deviation uncertainties (in percent) for LSD emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	9	11
NMHC	34	50	17
NOx	29	30	27
CO	111	144	78
PM10	45	39	50

1.5 *Viability and Functionality*

LSD is diesel fuel that meets either the Euro2 fuel specification for diesel fuel, or the fuel specification for LSD proposed by the Commonwealth for implementation in 2002. Reformulation of diesel to LSD requires no change to the current diesel distribution system or engines.

Changing diesel fuel composition and exhaust treatment can reduce emissions of toxic substances. Low sulfur content reduces emissions of PM. Reducing the polycyclic aromatic hydrocarbons and aromatic content reduces the emissions of some, but not all polycyclic aromatic hydrocarbon compounds. For heavy vehicles these changes do not reduce emissions of gaseous toxics such as formaldehyde, benzene, and 1,3 butadiene (different results are obtained from light vehicle emissions). Particle traps in conjunction with low sulfur fuels reduce emissions of organic compounds and particulate matter, but not always to the same degree. Although the emissions of toxics are lower, the limited data does not indicate that the kind of substances emitted, or the profile of toxic substances, are altered.

According to a news report in the Australian Financial Review (8 January 2001, page 4) the Royal Automobile Club of Queensland advised owners of affected diesel-engined vehicles to lodge compensation claims for fuel pump seal leaks resulting from the use of LSD refined in Brisbane. We are advised (M. Sanders, pers. comm.) that the problem was due to lowering of the aromatics content of the fuel. The rubber oil seals in pre-1994 Japanese diesel vehicles use a type of rubber that expands with high aromatic content. The sudden drop in aromatics associated with the transition to LSD caused the seals to shrink and led to fuel leakage. Similar problems also occurred with certain pieces of agricultural machinery.

BP will rectify the problem by paying for new seals. The problems did not arise as a result of the lowering of the sulfur content as such, but because of the use of a hydro-cracker instead of a hydro-refiner.

1.6 Health and OHS

1.6.1 Production and transport

Estimated trace metal emissions to air for particulate matter from refinery operations are shown in Table 1.7. The emitted metals include nickel, copper, zinc, selenium, antimony, lead, cadmium and mercury.

Estimates of organic (including benzene, toluene and xylene) and trace metal emissions to water in refinery effluent are in Table 1.9 and Table 1.10.

Particles

The estimated PM bus emissions during production and transport taken from Beer et al. (2000) is 0.17 g/km. The use of more recent Australian data (Table 1.25) has reduced this figure to 0.10 g/km. The urban precombustion (truck) PM10 estimate from this LCA is 43 mg/km, as given in Table 1.22.

Air Toxics

Refinery equipment fugitive emissions leaks for NPI estimated as a percentage of total VOC released are in Table 1.8. The estimated percentages of VOC are:

Xylene: 0.28

Benzene: 0.14

Toluene: 0.7.

The LSD upstream emissions estimate of non-methanic volatile organic compounds (NMVOC) taken from Beer et al. (2000) is 2.01 g/km. The use of more recent Australian data (Table 1.25) has reduced this figure to 1.09 g/km. The urban precombustion (truck) NMHC estimate from the LCA is 0.292 g/km, as given in Table 1.22.

An accompanying disk to this report provides details, on a per km basis, of air toxics emissions from upstream activities.

1.6.2 Use

Particulate matter

Beer et al. (2000) found that PM combustion emissions from LSD from a Swedish Euro2 bus were 0.200 g/km. The use of more recent Australian data (Table 1.26) has led to an estimate of 0.68 g/km. The combustion (truck) PM10 estimate from this LCA is 0.038 g/km, as given in Table 1.23.

Air Toxics

The use of more recent Australian data (Table 1.26) has led to an estimate for buses of 1.62 g/km of NMVOC. Emissions are given for the other air toxics, however, no data was available for toluene and xylene combustion emissions. There is a substantial difference between the APACE 1999 Sydney bus results for HC and those reported in the Stage 1 Report of Beer et al. (2000). The combustion (truck) HC (assumed to be equivalent to NMVOC) estimate from the LCA is 0.900 g/km as given in Table 1.23.

1.6.3 LSD emissions summary

The LCA emissions analysis given in Section 1.4 indicates that:

- The primary source of CO emissions is during the fuel production phase.
- The primary source of NOx emissions is during the combustion phase.
- The primary source of NMHC emissions is during the fuel production phase.
- The primary source of PM emissions is during the combustion phase. The combustion (truck) PM10 estimate of 38 mg/km will be used in comparisons with the other fuels.
- There is considerable variability in estimates of combustion HC emissions for LSD. This complicates comparisons between LSD and the various fuels in the absence of more detailed air toxics data. The combustion (truck) HC (assumed to be equivalent to NMVOC) estimate from the LCA of 0.900 g/km will be used in comparisons with the other fuels.
- Benzene emissions are estimated at 0.002 g/km
- 1,3 butadiene emissions are estimated at 0.017 g/km
- Formaldehyde and acetaldehyde emissions are very variable.
- polycyclic aromatic hydrocarbon emissions are estimated at 0.076 g/km

1.6.4 OHS issues

Diesel is hazardous according to Worksafe Australia criteria, with moderate toxicity, a moderate hazard in relation to body contact, and a moderate hazard in relation to chronic effects. It is less hazardous than petrol, but as refineries produce both petrol and diesel from crude oil, many of the precautions needed to guard against the high flammability of petrol are also needed during the manufacture of diesel.

Long-term occupational exposure of workers in refineries can lead to lympho-haematopoietic cancers, which include leukaemia, multiple myeloma, and non-Hodgkin’s lymphoma. The Health Watch study of refinery workers (Bisby, 1993) found that the incidence of these diseases in ex-refinery workers was twice that expected in the general population.

The OHS issues in the lifecycle of LSD are covered by a range of State and Commonwealth occupation health and safety provisions.

Vapour Pressure Issues

There are minimal evaporative emission issues during the transport and use of LSD due to its relatively low volatility.

Evaporative emissions are a considerably more important issue for petrol- or gasoline-fuelled vehicles, compared with diesel vehicles. There is evidence (see for example NRC, 1991) that evaporative emissions from petrol vehicles have been consistently under-estimated, and recent studies have continued to demonstrate the importance of evaporative emissions.

1.7 Environmental Impact

Ecologically sustainable development is based on the principles of equity, efficiency and ecological integrity. The modern western economy is based on petroleum products, of which diesel is one. Though substantial arguments can be advanced that such an economy is not sustainable, in the sense that fossil fuels constitute a non-renewable resource, over the past three decades exploration activity has continually discovered new hydrocarbon reserves. In addition, the current concern over climate change has highlighted the burning of fossil fuels as one of the main causes. Thus even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity.

Diesel is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from diesel itself can also occur, especially from leaks at service stations and refuelling depots that have been known to contaminate groundwater supplies.

1.8 Process trees

Figure 1.2 and 1.3 indicate process trees obtained from the SimaPro software used to undertake the quantitative life-cycle components of the study. These trees indicate, in an abbreviated form, the upstream components used to evaluate each component of the life-cycle.

To interpret the process tree, one starts at the top. Thus, in Figure 1.2, the values in the box refer to the mass (in kg) of CO_2-equ. To travel 1 km using LSD, there is a total of 0.926 kg emitted, as shown in the top box and summarised in Table 1.21. The fuel energy expended in travelling this 1 km is 10.8 MJ, as depicted in the second box down. The box below, which we shall call the fuel box, indicates that prior to combustion, the fuel tank contained 0.251 kg of fuel and that the upstream emissions of CO_2-equ to manufacture this fuel amounted to 0.207 kg CO_2-eq., as shown in Table 1.22.

Two separate process trees are depicted below the fuel box. The left hand side shows the upstream emissions involved in refining crude oil to produce diesel fuel. The process tree on the right shows the upstream emissions involved in hydro-processing to reduce the sulfur content of the fuel. For clarity, not all upstream processes are shown. If various upstream processes are not included, this is apparent by examining the bottom of the box. Small lines (tick marks) indicate that the full analysis consists of upstream processes feeding in to that box.

The computer software produces output in colour. On the right of each box there is a green line, with a red lower portion. The red lower proportion represents the proportion of the total value (0.926) accumulated up to that point. This can be seen by carefully examining the fuel box. The bottom 20% of the bar on the right of the box is darker than the remainder. The two top boxes have bars that are completely red.

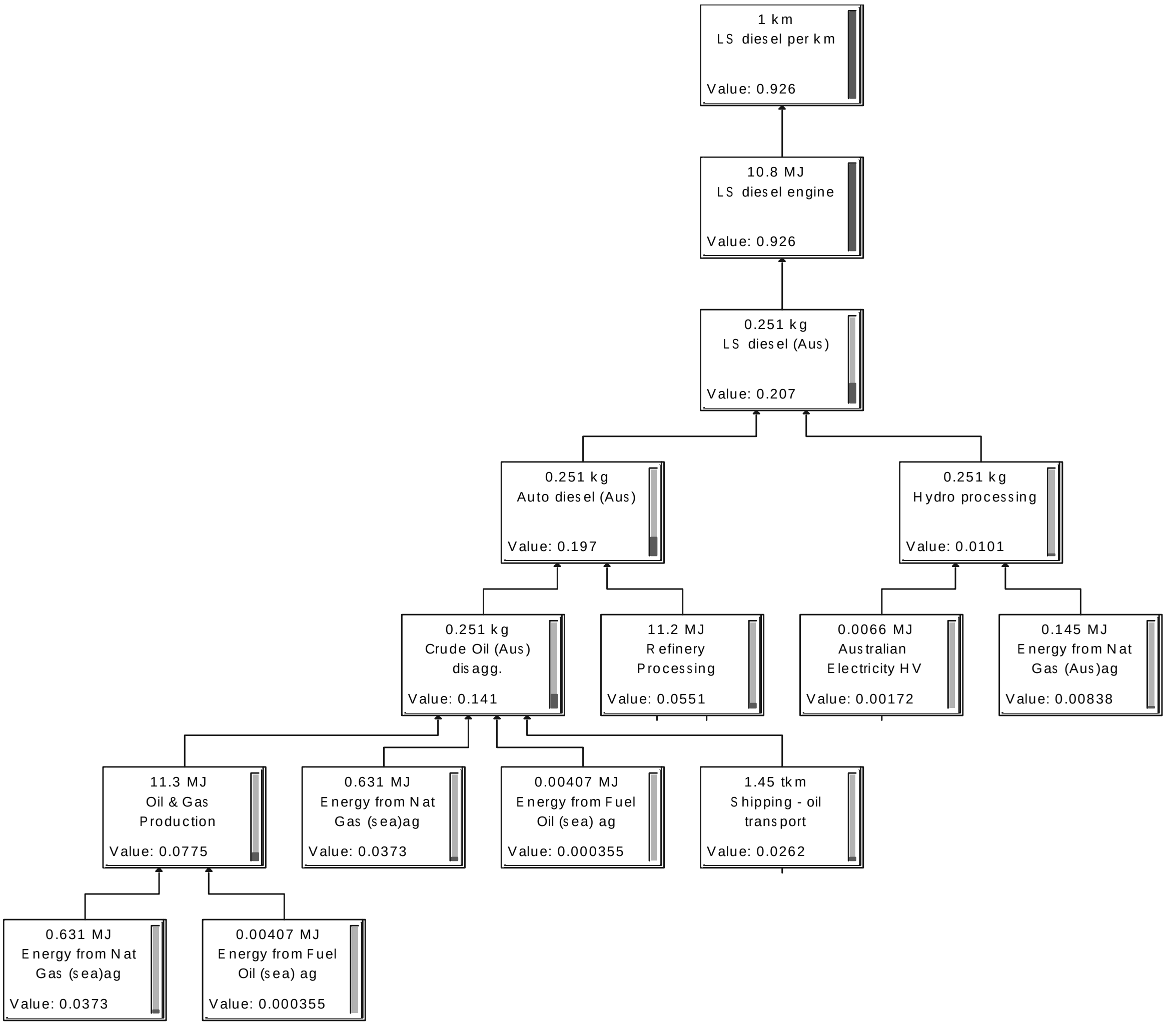

Figure 1.2
Exbodied greenhouse gases emissions (kg CO_2-eq) from LSD production, processing and use in vehicle. The value is given in the bottom of each box.

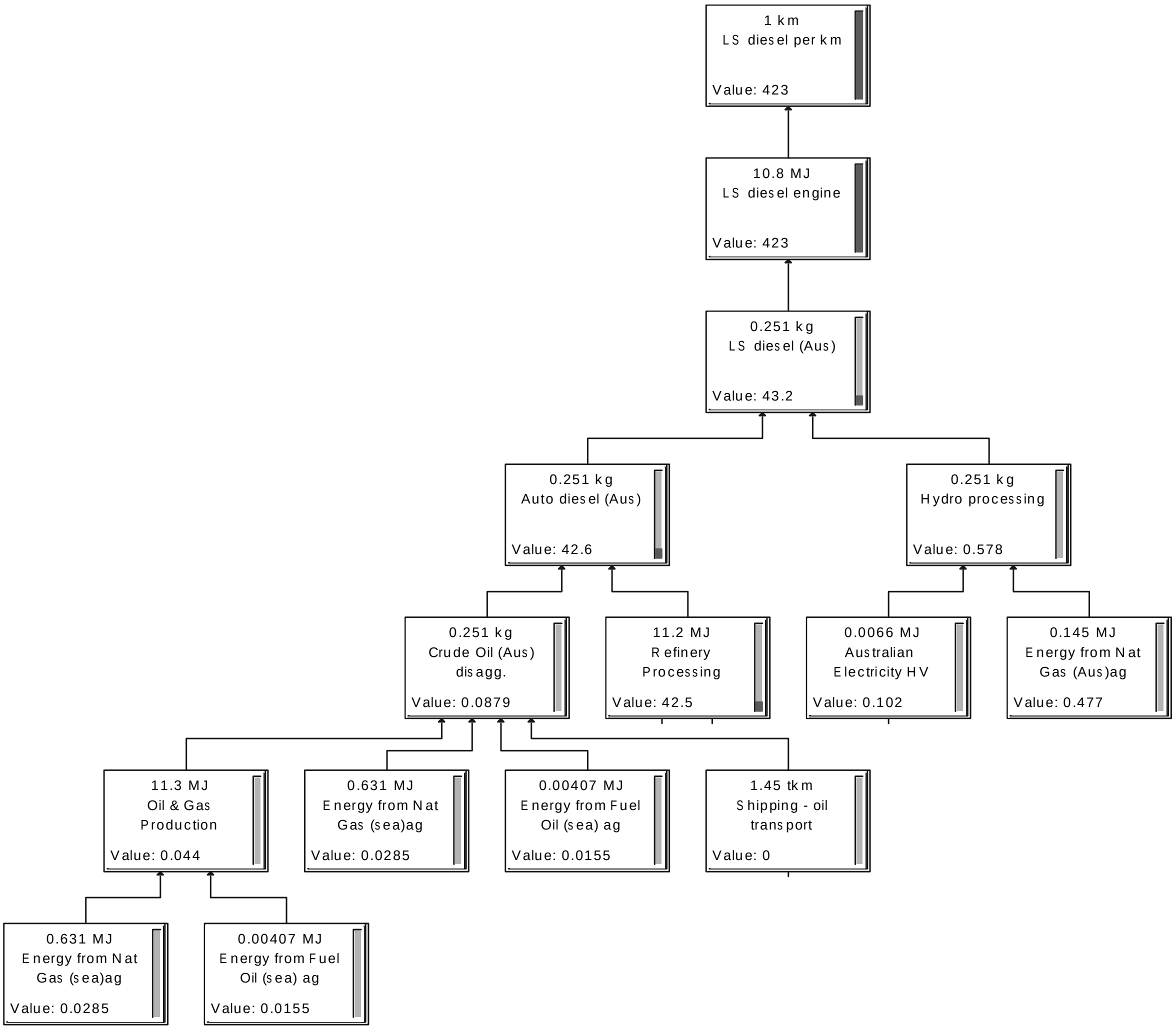

Figure 1.3
Exbodied particulate matter (mg - urban) from LSD production, processing and use.
The value is given in the bottom of each box.

2. Ultra-Low Sulfur Diesel

2.1 Background

Ultra-low sulfur diesel (ULSD) is diesel fuel that meets either the Euro4 fuel specifications for diesel fuel, or the fuel specifications proposed by the Commonwealth for implementation in 2006. To date, the only Euro4 fuel specification that has been established is for sulfur. Directive 98/70/EC of the European Communities in 1998 set the maximum sulfur level from 2005 as being 50 ppm. Euro3 specifications for other parameters such as the cetane number, cetane index, density, T95, and PAH levels, apply until replaced by revised specifications. These limits are shown in Table 2.1.

Table 2.1
Ultra-low sulfur diesel fuel quality specifications (Environment Australia, 2000a, 2000b)

Fuel parameter	Euro 3 (applicable from 2000)	Euro 4 (applicable from 2005)	Commonwealth (1 January 2006)
Sulfur (ppm)	350 (max)	50	50 (max)
Cetane number	51 (min)	-	-
Cetane index	46 (min)	-	50 (min)
Density at 15^{o}C (kg/m^3)	845 (max)	-	820 to 850
Distillation T95 (^{o}C)	350 (max)	-	360 (max)
PAH (% by mass)	11 (max)	-	11 (max)

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. Low sulfur diesel is produced in refineries with a hydro-desulfurisation unit. ULSD requires either a hydrocracker, or the use of higher pressures in the hydro-desulfurisation unit (hydrofining).

Greenhouse gas emission factors for diesel fuel may be found in Workbook 3.1 on transport of the Australian Greenhouse Gas Inventory methodology (National Greenhouse Gas Inventory Committee, 1998). A CO_2 emission factor of 69.7 g/MJ for diesel fuel (energy density of 38.6 MJ/L) is given in Workbook 3.1, whereas, for other emissions, the default emission factors are as given in Table 2.2.

Table 2.2
Emission factors for diesel vehicles expressed as g/km

Vehicle	CH_4	N_2O	NOx	CO	NMVOC
Light trucks	0.01	0.014	1.18	1.11	0.53
Medium trucks	0.02	0.017	3.1	1.82	0.99
Heavy trucks	0.07	0.025	15.29	7.86	3.78
Buses	0.03	0.025	4.9	2.88	1.56

Source: National Greenhouse Gas Inventory Committee (1998)

The values given in the Australian Greenhouse Gas Inventory are typical values representative of the Australian situation. They do not incorporate the possible changes to fuel properties arising from the different cetane values of LSD and ULSD produced by different refineries.

2.2 Upstream and Tailpipe Emissions

2.2.1 *Tailpipe emissions*

Parsons Australia Pty Ltd (2000) examined the emissions from a heavy truck using the CUEDC drive cycle using different diesel fuels of varying sulfur content. The results are given in Table 2.3, and these results are used in the subsequent calculations.

Table 2.3
Emissions and fuel consumption (FC) from a Euro 1 technology (ADR70) Rigid Truck (1995 Isuzu 900SUR) using a range of diesel fuels.

	S content mg/kg	CO_2 g/km	CO g/km	NOx G/km	HC g/km	PM (filter) mg/km	FC L/100km
Base Fuel	1700	782	3.45	10.63	1.01	447	32.92
Euro2	480	719	2.48	10.17	0.9	380	30.18
Euro3	210	746	2.75	10.47	0.95	313	31.22
Euro4	39	718	3.13	8.66	0.73	284	30.53
WorldWide	24	692	2.81	8.4	0.73	283	29.6
Californian diesel (CARB)	264	775	2.63	8.57	0.84	300	31.56

Source: Parsons Australia Pty Ltd (2000: Table 5.4)

The latest (and only other) Australian study of the heavy vehicle emissions from the use of ultra-low sulfur fuel was provided by BP Australia, namely that of Morawska et al. (2001). This report looked at the emission characteristics of LSD and ULSD used in a Volvo FL12 truck engine at constant speed. Three trucks were examined. Truck T3 had a catalytic converter, whereas trucks T1 and T2 did not. Table 2.4 summarises the Mode 5 data (50% load), by averaging the Western Australian and Queensland lower sulfur and ultra-low sulfur fuels for Trucks 1 and 2 for LSD and ULSD, and using the single reading for truck 3 for LSD+C, and ULSD+C.

Table 2.4
Emissions from Volvo FL12 trucks using low and ultra-low sulfur diesel fuel without and with (+C) a catalytic converter

	PM10 (mg/km)	CO_2 (g/km)	NOx (g/km)
LSD	729	1927	12
LSD+C	479	1677	7
ULSD	576	1958	11.5
ULSD+C	509	2009	9

2.2.2 *Upstream*

Production of low sulfur and ultra-low sulfur diesel

Diesel fuel is manufactured using crude oil as a feedstock. Depending on the characteristics of the crude oil(s) used, a number of different refinery streams may be blended to produce diesel fuel complying with the relevant specification. These streams most commonly include straight run distillate, light cycle oil (LCO) produced from heavier fractions in a fluid catalytic cracker (FCC) and vacuum gasoil (VGO). Sulfur contents of these fractions depends on the feedstock crude oil used and may be as high as 2%, and their boiling range falls between 150°C and 380°C. Refineries may be configured in many ways, depending on the properties of the crude oil feedstock and desired products spectrum. An example flow diagram of crude oil processing is presented in Figure 2.1.

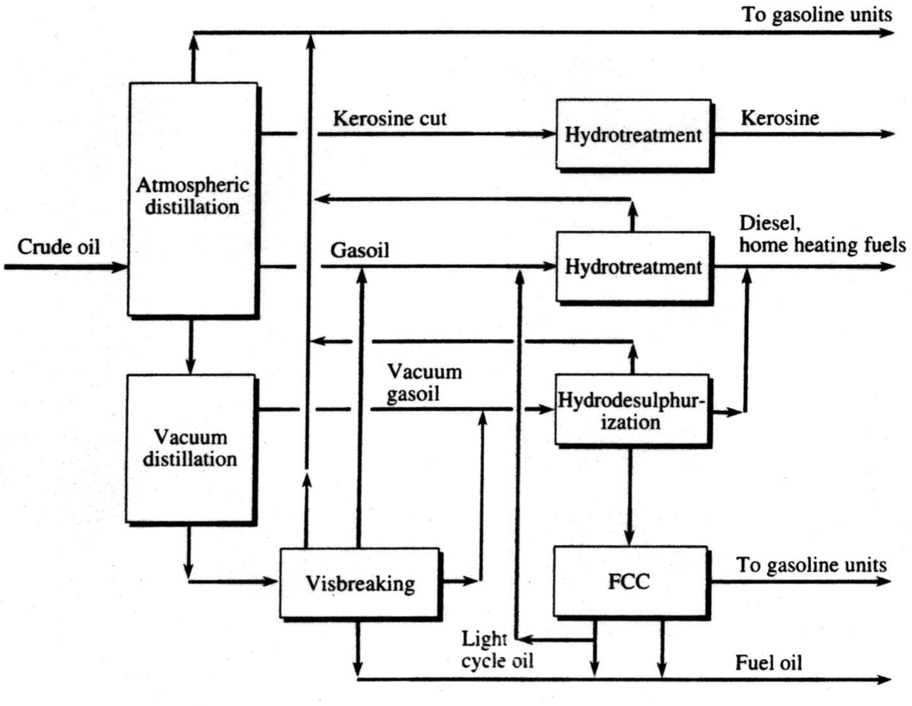

Figure 2.1
Typical flow-chart for crude oil processing

Diesel fuel currently used in Australia has a sulfur content of around 1300 ppm. As from 31 December 2002, new low sulfur diesel specifications will apply requiring the sulfur content of diesel fuel to be lower than 500 ppm. From 1 January 2006 ULSD will be required.

High levels of sulfur in diesel fuel are undesirable as during the combustion process they are converted to volatile sulfur oxides (SOx). These are corrosive and lead to increased engine wear. They also contribute directly to acid rain and produce solid sulfates, which add to the particulate matter in the exhaust gases.

Hydrodesulfurisation (HDS) is the process that is used to reduce sulfur. The process involves catalytic hydrogenation, which converts chemically bound organic sulfur into hydrogen sulfide (H_2S). It also improves the cetane number.

To meet the 500 ppm limit, a single stage HDS unit using Cobalt-Molybdenum (Co-Mo) and sometimes Nickel-Molybdenum (Ni-Mo) catalyst under moderate severity is adequate. Typical configuration of a HDS unit is shown in Figure 2.2.

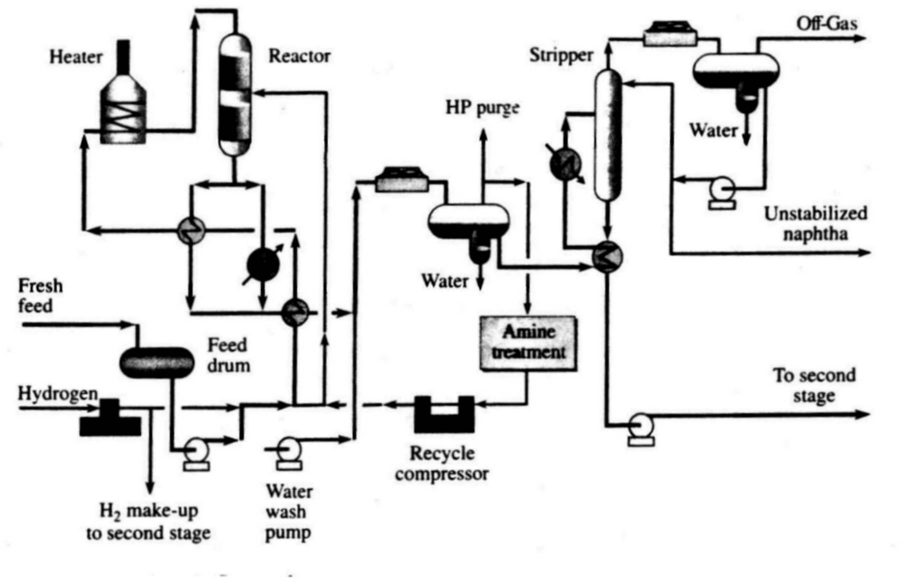

Figure 2.2
Flow diagram of single stage HDS unit

Further sulfur removal (down to below 50 ppm in the case of ULSD) requires a two-stage, high severity HDS unit using the Co-Mo catalyst in the first stage and Ni-Mo catalyst in the second stage. Hydrogenation of diesel over Co-Mo catalyst removes mostly sulfur associated with aliphatic hydrocarbons, while more active Ni-Mo catalyst facilitates hydrogenation of aromatic sulfur as well as saturation of aromatic hydrocarbons thus increasing cetane number and changing physical properties of resulting diesel such as viscosity and cloud point.

Basic assumptions on diesel production

Energy use for oil and gas production and transportation, and refinery processing is taken from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000) and are shown in Table 2.5.

We assume, based on Australian refinery practice, that the only difference in the energy used to process diesel, LSD and ULSD occurs during hydro-desulfurisation. Thus, we assume oil and gas are produced together and emissions and extraction energy are allocated between them based on the energy content of each fuel. Similarly, refinery products, such as diesel, LSD, ULSD, petrol, LPG and so on, are treated as co-products with the energy consumption, and consequent emissions being allocated to the output products (diesel, petrol, LPG), based on the energy content of each fuel.

Table 2.5
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use (PJ)	Production 1998[3] (PJ)	Energy use to energy production ratio (GJ/PJ produced)
Oil and gas production and field processing	Petroleum	0.9[1]	2528.6	0.36
	Gas	141.1[1]	2528.6	55.80
Natural gas transmission	Gas	8.6[1]	688.5	12.49
Gas production and distribution	Gas	2.4[1]	371.5	6.46
Petroleum Refining	Petroleum	87.2[2]	1663.8	52.41
	Gas	11.6[2]	1663.8	6.97

[1] Fuel Combustion Activities 1A-2 (sheet 1): Emissions from manufacturing industries and construction (all sources) (NGGICf)

[2] Fuel Combustion Activities 1A-1 (sheet 2): Emissions from Energy Industries (all sources) (NGGIC)

[3] Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas (NGGIC)

Emissions from combusted fuels and fugitive emissions are also taken from the National Greenhouse Gas Inventory and are shown in Table 2.6. No Australian aqueous emission or solid wastes data was available for the crude oil, natural gas production or transport sectors, so data from European studies (Boustead, 1993) has been used as a proxy. This data is detailed in Table 2.7 and Table 2.8

Table 2.6
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO_2	CH_4	N_2O	NOx	CO	NMVOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	0	168	2.6		0.1	0.5	93.6
	Crude oil production	1257	14.8	0.2				0.1
	Crude oil transport: domestic	298		0.3				0.3
	Crude oil refining and storage	1664		0.2				1.3
	Petroleum product distribution	1102	153	1.9		0.1	0.5	34
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for Oil and Gas Production	Venting at Gas processing plant	1272	2814	119.6				42.3
	Distributed Venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

Table 2.7
Aqueous emission for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Acid as H+	1.56	0.53
Metallic ions	0.19	0.09
CxHy	0.19	0.09
Suspended solids	1.56	0.71
Dissolved solids	1.36	0.18
Dissolved organics	0.78	0.36
Oil	1.36	0.53
Phenol	0.02	0.02

Source (Boustead, 1993)

Table 2.8
Aqueous emission for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Industrial waste	0.78	0.71
Mineral waste	0.08	0.07
Slags/ash	11.70	10.67
Inert chemicals	0.39	0.36

Source (Boustead, 1993)

For refineries, data on trace metals and volatile organic fugitive emissions was taken from the National Pollutant Inventory Guide book (Environment Australia 1999b), together with data submitted by refineries to the National Pollutant Inventory.

The controlled emission factor for particle emission from fluid catalytic cracking units is taken as 0.128 (Environment Australia, 1999b; Table 10, page 19). From this data, trace metal emission data are estimated using emission factors provided in the NPI guidebook (Environment Australia, 1999b: Table 11, page 20), which are shown in Table 2.9.

Table 2.9
Metal emissions to air for particulate matter from refinery operations

Metal emission	Controlled emission factor as weight % of total particulate matter
Nickel	0.031
Copper	0.003
Zinc	0.006
Selenium	0.003
Antimony	0.002
Lead	0.01
Cadmium	0.002
Mercury	0.001

Source: Extracted from Environment Australia (1999b: Table 11 p. 20)

Volatile organic emissions were estimated using emission factors related to total VOC emission from fugitive emission in refineries, given in the NPI guidebook (Environment Australia 1999b: Table 15 page 31). Data was given for a range of fugitive leaks such as flanges, valves, drains and pump seals. The lowest and most common was the data for flanges and valves, so this data was used to break down the VOC emission reported in the National Greenhouse Gas Inventory into different organic species as shown in Table 2.10.

Table 2.10
Speciation Data for NPI Substances from Equipment Fugitives[1]

Compound	Compound Weight Percent in VOCs Released
n-hexane	4.76
Cyclohexane	0.14
Xylenes	0.28
Benzene	0.14
Toluene	0.7

Source: Extracted from (Environment Australia 1999b: Table 15 page 32)

[1] Emission factors are for flange and valves

Organic and trace metal emission to water were also determined from data in the NPI Guide. Metal emissions are provided per cubic metre of waste water (Environment Australia 1999b: Table 20 page 41), while organic emission are provided as a weight percent of dissolved organic carbon (Environment Australia 1999b: Table 19 page 40. Waste water effluents and DOC loads per tonne of production were estimated from reported emission data from refineries to the National Pollutant Inventory. The data was conservatively estimated by dividing total flow by capacity, rather than production. This would have the effect of reducing the data on a per tonne basis. Emission factors for organics to water are presented in Table 2.11 while factors for metals emitted are provided in Table 2.12. The calculated average wastewater emission for Australian refineries was 30 L per tonne of product and the dissolved organic carbon (DOC) was calculated to be around 0.79 g per tonne of product.

Table 2.11
Default Speciation Factors for Organics in Refinery Effluent

Organic substance	NPI Substance Weight Percent of DOC
Toluene	0.00092
Benzene	0.00091
Xylenes	0.00140
Phenol	0.00069
1,2-Dichloroethane	0.00027
Hexachlorobenzene	0.00000
PAHs	0.00160
Styrene	0.00010
Ethylbenzene	0.00012
1,1,2-trichloroethane	0.00004
Chloroform	0.00250

Source: Environment Australia 1999b: Table 19 page 40

Table 2.12
Default Emission Factors for Trace Elements and Inorganics in Refinery Effluent

Trace Elements	NPI Substance Emission Factors (kg/m^3 of flow)
Zinc	4.40E-04
Phosphorous	4.10E-07
Arsenic	6.70E-06
Chromium(VI)	7.70E-06
Selenium	3.10E-06
Nickel	3.60E-06
Copper	2.90E-06
Antimony	5.80E-07
Cobalt	1.60E-06
Mercury	1.10E-08
Cadmium	3.30E-07
Lead	1.90E-06
Cyanide	7.60E-09
Ammonia	1.30E-06

All energy use throughout fuel processing is assumed to have a greenhouse emission profile as of standard fuel combustion as described in the National Greenhouse Gas Inventory in Fuel Combustion Activities 1A-1 (sheet 1): Emissions from Energy Industries (all sources) (NGGIC 1998). Air emissions of organic and inorganic substances, and particles are taken from the National Pollutant Inventory Emission Estimation Technique Manual for Combustion in Boilers (Environment Australia 1999a). Grid supplied electricity data is taken from the Australian LCA inventory data project, described in (Grant 2000).

Assumptions for production of low sulfur diesel

Discussions with Mr Mark Sanders of BP, an expert in refinery operation, updated the previous assumptions that were made regarding additional processing to produce lower sulfur diesel. For low sulfur diesel (500ppm S) a hydro-desulfurisation unit would be required on top of current refinery operations. Beer et al. (2000) assumed that for ultra-low sulfur fuel a hydrocracking unit would be required on top of normal refinery operations. More recent information indicates that existing hydrofiners can be used to produce ULSD by employing more active catalysts, increased hydrogen purity, and reduced space velocities. In the absence of better data, information on the two processes has been taken from standard equipment specifications. The data for this is shown in Table 2.13. The life-cycle calculations have been undertaken for existing Australian conditions with 50% of ULSD from a hydro-desulfurisation unit and 50% of ULSD from a hydrocracking unit. In addition, a second scenario (marked as 100% hydroprocessing) calculates emissions if all Australian refineries use only hydro-desulfurisation units.

Table 2.13
Additional inputs to produce 1 tonne LSD and ULSD from 1 tonne current diesel

	Equipment	Electricity	Energy from Gas oil	Steam
		kWh	MJ	kg
Low Sulfur	Hydro-desulfurisation unit	7.3	577	0
Ultra-low Sulfur	Hydrocracking Unit	50.3	1578	95

Source: J. Hydrocarbon Processing. (supplied by M. Sanders, pers. comm.)

2.3 Results

2.3.1 Emissions per unit energy

Table 2.14
Urban and total life cycle emissions per MJ calculated for low and ultra-low sulfur diesel

Full Lifecycle	Units (per MJ)	LS diesel	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.0858	0.0881	0.0877
NMHC total	g HC	0.140	0.128	0.131
NMHC urban	g HC	0.111	0.097	0.098
NOx total	g NOx	1.044	0.915	0.909
NOx urban	g NOx	0.987	0.855	0.844
CO total	g CO	0.253	0.314	0.313
CO urban	g CO	0.242	0.303	0.301
PM10 total	mg PM10	40.7	31.9	32.2
PM10 urban	mg PM10	39.3	30.4	30.6
Energy Embodied	MJ LHV	1.18	1.27	1.34

Table 2.15
Urban and total precombustion emissions per MJ for low and ultra-low sulfur diesel

Precombustion	Units	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.0191	0.0222	0.0218
NMHC total	g HC	0.0565	0.0614	0.0642
NMHC urban	g HC	0.027	0.030	0.031
NOx total	g NOx	0.100	0.120	0.114
NOx urban	g NOx	0.043	0.060	0.049
CO total	g CO	0.023	0.027	0.026
CO urban	g CO	0.012	0.016	0.014
PM10 total	mg PM10	5.42	5.84	6.16
PM10 urban	mg PM10	4	4.33	4.55
Energy Embodied	MJ LHV	1.18	1.27	1.34

Table 2.16
Urban and total combustion emissions per MJ for low and ultra-low sulfur diesel

Combustion	Units	LSD	ULSD
Greenhouse	kg CO_2	0.067	0.066
NMHC total	g HC	0.084	0.067
NMHC urban	g HC	0.084	0.067
NOx total	g NOx	0.944	0.795
NOx urban	g NOx	0.944	0.795
CO total	g CO	0.230	0.287
CO urban	g CO	0.230	0.287
PM10 total	mg PM10	35.26	26.08
PM10 urban	mg PM10	35.26	26.08
Energy Embodied	MJ LHV	0	0

Table 2.17
Summary of life cycle emissions per MJ for ultra-low sulfur diesel

		LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	Precombustion	0.0191	0.0222	0.0218
Greenhouse	Combustion	0.0667	0.0659	0.0659
NMHC total	Precombustion	0.0565	0.0614	0.0642
NMHC total	Combustion	0.0835	0.0670	0.0670
NMHC urban	Precombustion	0.0271	0.0297	0.0308
NMHC urban	Combustion	0.0835	0.0670	0.0670
NOx total	Precombustion	0.1000	0.1200	0.1140
NOx total	Combustion	0.944	0.795	0.795
NOx urban	Precombustion	0.043	0.060	0.049
NOx urban	Combustion	0.944	0.795	0.795
CO total	Precombustion	0.0225	0.0270	0.0256
CO total	Combustion	0.2301	0.2874	0.2874
CO urban	Precombustion	0.0123	0.0159	0.0139
CO urban	Combustion	0.2301	0.2874	0.2874
PM10 total	Precombustion	5.42	5.84	6.16
PM10 total	Combustion	35.26	26.08	26.08
PM10 urban	Precombustion	4.00	4.33	4.55
PM10 urban	Combustion	35.26	26.08	26.08
Energy Embodied	Precombustion	1.18	1.27	1.34

2.3.2 *Emissions per unit distance*

Table 2.18

Urban and total life cycle emissions per km calculated for low and ultra-low sulfur diesel

Full Lifecycle	Units (per km)	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.9250	0.9470	0.9270
NMHC total	g HC	1.509	1.363	1.346
NMHC urban	g HC	1.192	1.036	1.026
NOx total	g NOx	11.250	9.900	9.750
NOx urban	g NOx	10.638	9.275	9.133
CO total	g CO	2.723	3.408	3.376
CO urban	g CO	2.612	3.294	3.264
PM10 total	mg PM10	438.4	344.2	343.1
PM10 urban	mg PM10	423.1	328.6	327.6
Energy Embodied	MJ LHV	12.7	13.1	12.9

Table 2.19
Urban and total precombustion emissions per km for low and ultra-low sulfur diesel

Precombustion	Units (per km)	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.2060	0.2290	0.2090
NMHC total	g HC	0.609	0.633	0.616
NMHC urban	g HC	0.292	0.306	0.296
NOx total	g NOx	1.080	1.240	1.090
NOx urban	g NOx	0.468	0.615	0.473
CO total	g CO	0.243	0.278	0.246
CO urban	g CO	0.132	0.164	0.134
PM10 total	mg PM10	58.4	60.2	59.1
PM10 urban	mg PM10	43.1	44.6	43.6
Energy Embodied	MJ LHV	12.7	13.1	12.9

Table 2.20
Urban and total combustion emissions per km for low and ultra-low sulfur diesel

Combustion	Units	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.719	0.718	0.718
NMHC total	g HC	0.900	0.730	0.730
NMHC urban	g HC	0.900	0.730	0.730
NOx total	g Nox	10.170	8.660	8.660
NOx urban	g Nox	10.170	8.660	8.660
CO total	g CO	2.480	3.130	3.130
CO urban	g CO	2.480	3.130	3.130
PM10 total	mg PM10	380.00	284.00	284.00
PM10 urban	mg PM10	380.00	284.00	284.00
Energy Embodied	MJ LHV	0	0	0

Table 2.21
Summary of life cycle per km emissions from ultra-low sulfur diesel

		LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	Precombustion	0.2060	0.2290	0.2090
Greenhouse	Combustion	0.7190	0.7180	0.7180
NMHC total	Precombustion	0.6090	0.6330	0.6160
NMHC total	Combustion	0.9000	0.7300	0.7300
NMHC urban	Precombustion	0.2920	0.3060	0.2960
NMHC urban	Combustion	0.9000	0.7300	0.7300
NOx total	Precombustion	1.0800	1.2400	1.0900
NOx total	Combustion	10.170	8.660	8.660
NOx urban	Precombustion	0.468	0.615	0.473
NOx urban	Combustion	10.170	8.660	8.660
CO total	Precombustion	0.2430	0.2780	0.2460
CO total	Combustion	2.4800	3.1300	3.1300
CO urban	Precombustion	0.1320	0.1640	0.1340
CO urban	Combustion	2.4800	3.1300	3.1300
PM10 total	Precombustion	58.40	60.20	59.10
PM10 total	Combustion	380.00	284.00	284.00
PM10 urban	Precombustion	43.10	44.60	43.60
PM10 urban	Combustion	380.00	284.00	284.00
Energy Embodied	Precombustion	12.70	13.10	12.90

2.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 2.22.

Table 2.22
Estimated one standard deviation uncertainties (in percent) for ultra-low sulfur diesel emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	9	11
NMHC	34	50	17
NOx	29	30	27
CO	111	144	78
PM10	45	39	50

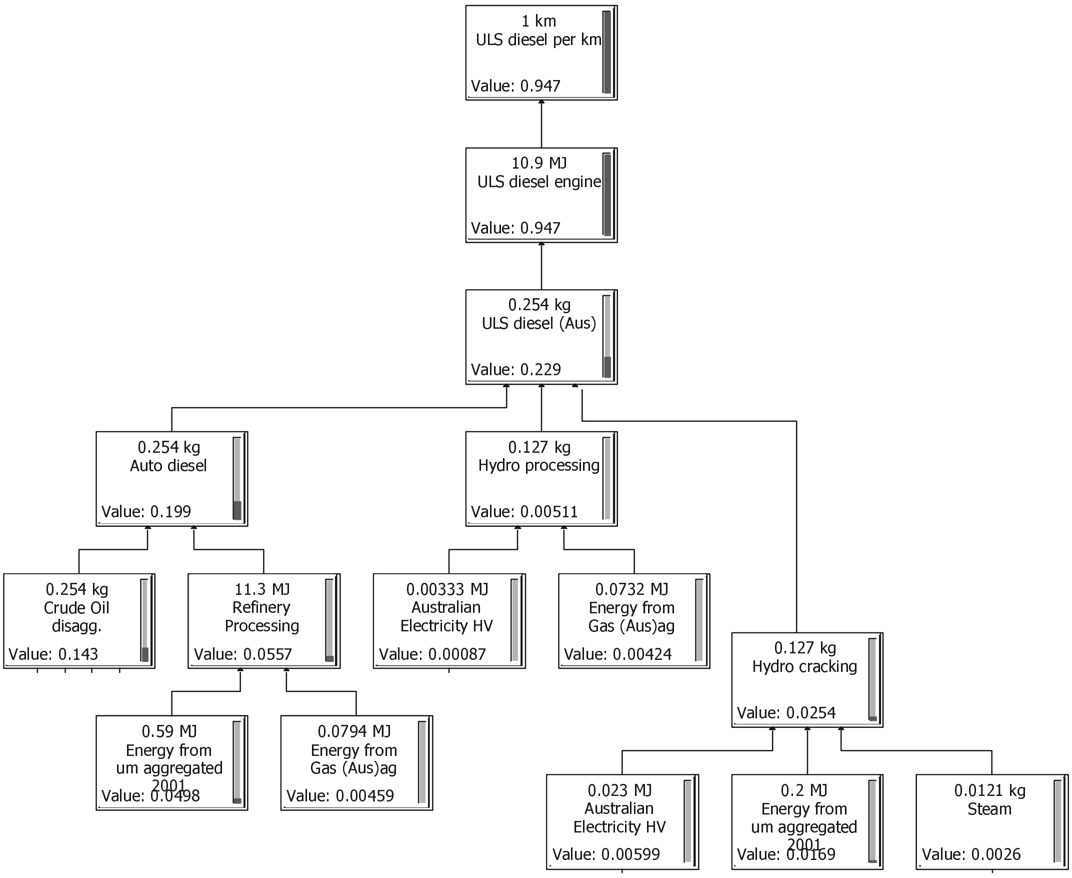

Figure 2.3
Exbodied greenhouse gases emissions (kg CO_2eq) from ULS diesel production and processing and use in vehicle (50% produced using hydro-cracking unit)

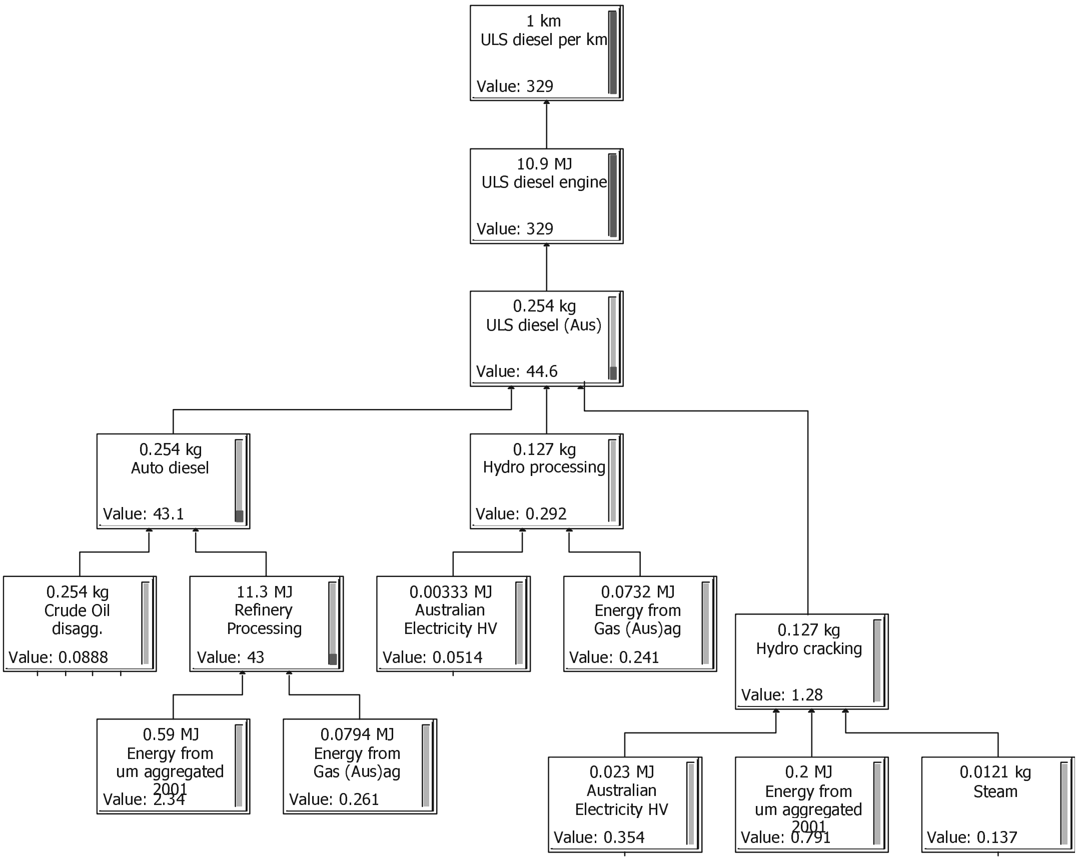

Figure 2.4
Exbodied particulate matter (mg - urban) from ULS diesel production and processing and use in vehicle (50% produced using hydro-cracking unit)

2.4 Viability and Functionality

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on engine performance arising from the introduction of low sulfur diesel and ULSD. The comments in the fuel quality review are echoed by the submissions that were received as part of this study. The Federal Chamber of Automotive Industries (FCAI) notes that in the case of low sulfur diesel 500 ppm is regarded as far too high. Sulfur levels of 100 ppm or less will be needed to ensure that exhaust after-treatment systems function efficiently and allow successful development of clean diesel engines that can realise the inherent fuel efficiency of diesel engines. With respect to ULSD, the FCAI consider the 50 ppm sulfur level as still being too high in terms of providing satisfactory exhaust emissions expected of low emission diesel engines.

BP Australia emphasise the need to match the fuel with the appropriate vehicle technology. They point out that the major benefits of the move to ULSD are provided by the ability to use advanced technology in the engine and the catalyst. These components are often sensitive to sulfur. Therefore it is essential to show the vehicle emissions that are possible with the appropriate Euro4 fuelled engines once both the fuels and the vehicles are available, as is expected to be the case within the next five years. Using ULSD in a Euro2 vehicle will provide only marginal improvement in tailpipe emissions over low sulfur diesel. However, the emissions from a Euro4 vehicle with advanced on-board diagnostics and a particle trap are expected to be dramatically better.

2.5 Health Effects

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on health effects arising from the introduction of low sulfur diesel and ULSD. This report points out that diesel engines are a major source of fine particles – diesel exhaust releases particles at a rate about 20 times greater than that from petrol-fuelled vehicles. Thus the combination of ULSD and particle traps on vehicles using ULSD will reduce the emissions of particles.

The reduction in the number of particles will have two beneficial effects. It will assist in the attainment of the national ambient air quality standard for particles. In addition, diesel engine exhaust contains both small carbonaceous particles and a large number of chemicals that are absorbed onto these particles. The fuel quality review cites studies that have indicated that diesel particles are mutagenic and carriers of compounds that are suspected of contributing to the rise in cancer cases in city areas with a large proportion of diesel-fuelled vehicles.

2.5.1 ***Production and Transport***

The upstream health issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

Particulate matter

The LCA estimate for ULSD urban precombustion (truck) PM10 emissions of 45 mg/km is similar to the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for ULSD urban precombustion (truck) NMHC emissions of 0.306 g/km is similar to the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

2.5.2 ***Use***

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ultra-low sulfur diesel. The combination of ULSD and oxygenating catalysts or “de-NOx” catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality.

2.5.3 ***Particulate matter***

The LCA estimate for ULSD combustion (truck) PM10 emissions of 284 mg/km is less than the LSD estimate of 380 mg/km.

2.5.4 Air toxics

Diesel fuel formulation appears to have little effect on emissions of VOCs and aldehydes, suggesting that the formation of these species in diesel exhaust is controlled by the combustion process. (Parsons Australia Pty Ltd, 2000)

The LCA estimate for ULSD combustion (truck) NMHC emissions of 0.73 g/km is similar to the LSD estimate of 0.9 g/km.

2.5.5 Summary

ULSD upstream particle and NMHC emissions are similar to LSD. ULSD tailpipe NMHC emissions are similar to LSD and have little effect on emissions of VOCs and aldehydes. ULSD reduces particle emissions compared to LSD.

2.6 OHS Issues

The upstream OH&S issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

2.7 Vapour Pressure Issues

The vapour pressure issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

2.8 Summary

The advantages of ultra-low sulfur diesel are:

- ULSD contains little sulfur and few aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The low sulfur content means that oxidation catalysts will be more efficient.
- The existing diesel infrastructure can be used, unchanged, for ultra-low sulfur diesel.
- Low-sulfur diesel can be used in existing diesel engines.
- Diesel is one of the safest of the automotive fuels.

The disadvantages of ultra-low sulfur diesel are:

- Diesel exhaust (including ULSD exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, ULSD produces more exbodied greenhouse gases than LSD.

2.9 Environmental Issues

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ULSD. The combination of ULSD and oxygenating catalysts or “de-NOx” catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality.

The upstream environmental issues associated with ULSD are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

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3. Fischer-Tropsch Diesel

3.1 *Introduction*

Fischer-Tropsch (FT) diesel is a synthetic fuel produced from the conversion of natural gas into a diesel fuel. The fuel thus formed is superior to crude oil based diesel in certain ways, principally the high cetane number and the zero sulfur content. It is also known as GTL diesel, where the acronym refers to “gas to liquid” conversion. Gas to liquid fuels conversion is of relevance to Australia, because of the large natural gas deposits in the North West Shelf.

The Fischer-Tropsch process has mainly been used during disruptions to crude oil supply. In Germany, during World War II, petrol and fuels were made from coal by the Fischer-Tropsch process. The only existing industrial scale Fischer-Tropsch refineries are in South Africa, built during the period of economic sanctions against the regime. Figure 3.1 shows Sasol’s synthetic petroleum facility process.

Exxon, Syntroleum (www.syntroleum.com) and Rentech (http://www.rentechinc.com/) are major US companies involved in Fischer-Tropsch, Gas-to-Liquids (GTL) conversion. Sasol Chevron (www.sasolchevron.com), which is headquartered in the UK, is considering Australia as the site of a US$1billion first stage synthetic fuels plant aimed at the diesel market. Shell is also involved with GTL. They and others have patented proprietary processes, for the conversion of synthesis gas made from natural gas, coal, refinery bottoms, industrial off-gas and other hydrocarbon feedstock into clean sulfur-free and aromatics-free alternative fuels, naphtha and waxes. Beside their clean emissions qualities for conventional vehicles, GTL fuels can be sources of energy for fuel cell feedstock. Sulfur-free GTL fuels will not contaminate fuels cells and contain approximately twice the hydrogen than does methanol, another candidate feedstock for fuel cells.

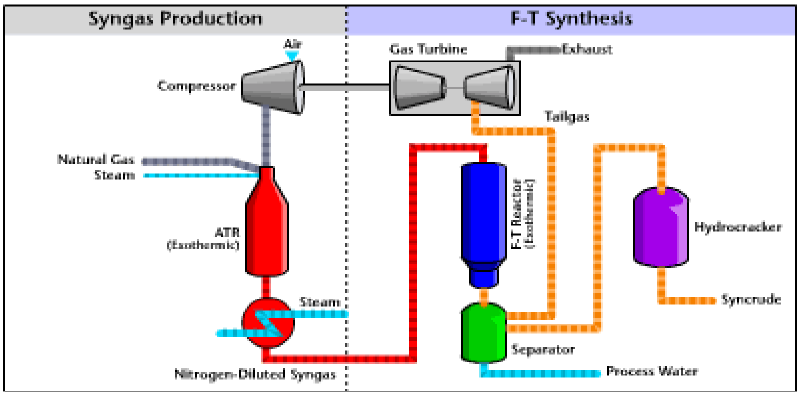

Figure 3.1
Schema for Syntroleum gas to liquid conversion facility
Source: http://www.syntroleum.com/sp1_gs.htm

There are a number of different options available for the implementing the Fischer-Tropsch process. Provided that a Fischer-Tropsch plant uses an oxygen feed then it produces a pure carbon dioxide stream. Such an implementation provides an option to collect and sequester the carbon dioxide.

This study is required to use Australian data where available. At the time of writing SASOL-Chevron was not in a position to submit emissions data that would be applicable to its production of FTD and the use of FTD in Australia. It is recommended that a separate study be undertaken when that data becomes available.

There have been some overseas studies that examined the full fuel-cycle (or well to wheel) emissions associated with Fischer-Tropsch diesel. Louis (2001) found that for passenger cars, exbodied greenhouse gas emissions associated with FTD were less than those of petrol, but greater than those of conventional diesel. Even though FTD produces slightly lower tailpipe emissions, the upstream emissions of greenhouse gases during the production of FTD are much greater than those emitted during production of diesel. General Motors Corporation (2001) obtained similar, though less dramatic, results. The General Motors study found significantly greater well to wheel energy usage, but only marginally greater exbodied greenhouse gas emissions.

3.2 Full Fuel Cycle Analysis

3.2.1 Upstream emissions

Production of Fischer-Tropsch diesel

The Fischer-Tropsch process produces a broad range of hydrocarbons using syngas (hydrogen and carbon monoxide mixture) as a feedstock. The products spectrum can be controlled by the choice of the catalyst, process configuration and operating conditions. Generally speaking, higher process temperatures (>320°C) and iron based catalysts favour the production of lighter hydrocarbons suitable for petrol production, while cobalt based catalysts and lower process temperatures (<250°C) tend to produce paraffins in the diesel and wax range.

Production of FTdiesel consists of three steps:

- Syngas production
- Hydrocarbons synthesis
- Product upgrading.

The overall process and delivery is outlined in Figure 3.2.

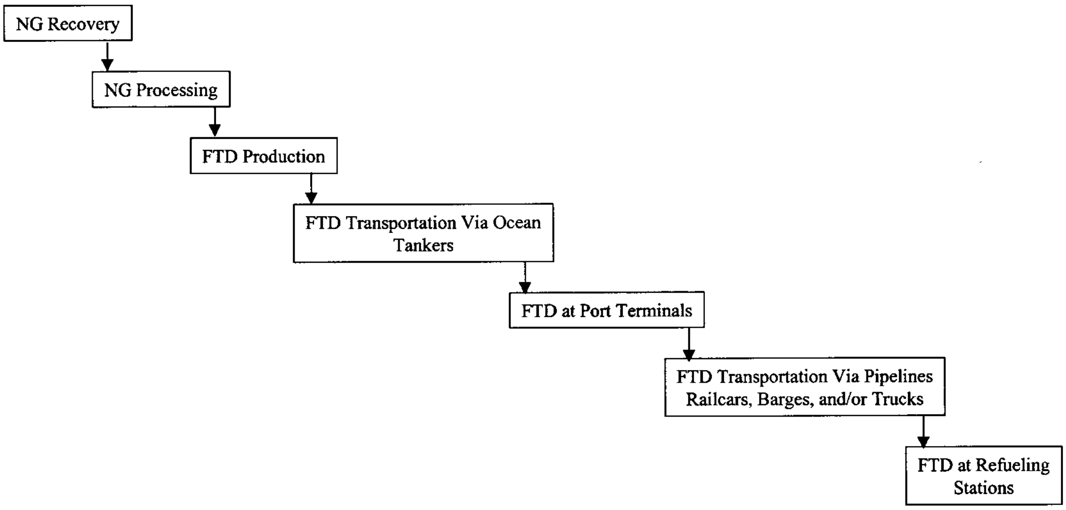

Figure 3.2
Flow diagram of Fischer-Tropsch diesel production and delivery.

Conversion of natural gas to syngas via steam reforming is described in the chapter on hydrogen production. However, syngas generated by the steam reformer tends to have H_2/CO ratio of about 3 as per reaction

Steam reforming reaction $CH_4 + H_2O = CO + 3H_2$

As an ideal H_2/CO ratio for Fischer-Tropsch process is about 2, an alternative syngas production process called partial oxidation is more often employed. It involves passing a mixture of desulfurised natural gas and pure oxygen (or air in the Syntroleum process) over a catalyst containing nickel or platinum group metal at temperatures above 900^oC. The reaction proceeds as per equation

Partial oxidation reaction $2CH_4 + O_2 = 2CO + 4H_2$

And the resulting syngas has H_2/CO ratio of 2. In some cases non-catalytic partial oxidation and/or auto-thermal reforming may be employed. Sasol Chevron uses auto-thermal technology at very low steam/carbon ratios.

Because natural gas feed for partial oxidation and syngas for the Fischer-Tropsch process should be free of sulfur to avoid catalysts poisoning, feed desulfurisation is required ahead of the partial oxidation reactor. The desulfurisation step usually consists of passing the sulfur-containing natural gas feed at about 300–400°C over a CoMo catalyst in the presence of 2–5% H_2 to convert organic sulfur compounds to H_2S. This is then followed by adsorption of H_2S over ZnO guard bed to reduce the sulfur level to less than 0.1 ppm wt which is the level that the oxidation and Fischer-Tropsch catalysts can tolerate.

The Fischer Tropsch synthesis reaction can be symbolically described by this equation:

Fischer-Tropsch synthesis $2nH_2 + nCO = n(\text{-}CH_2\text{-}) + nH_2O$

In the above equation, the expression $\text{-}CH_2\text{-}$ represents basic building block of the paraffin molecule. Straight chain paraffins are main products of the Fischer-Tropsch process configured for the production of the distillate, with minor quantities of isoparaffins and olefins also present in the products spectrum. Because of the paraffinic character, Fischer-Tropsch diesel has high cetane number and good combustion characteristics.

The reaction is carried out by passing syngas over cobalt based catalyst at temperatures between 180^oC and 250^oC at pressures between 2Mpa and 4Mpa. The Sasol process uses a slurry reactor where the catalyst is suspended in a hydrocarbon liquid, while the Shell process uses fixed bed reactor packed with catalyst pellets.

The product stream contains a broad range of hydrocarbons that require fractionation and processing. Light fractions, together with unreacted syngas are usually recycled. The naphtha fraction has to be reformed before being blended into petrol. Middle distillate does not require processing and constitutes high quality diesel fuel. Heavier fractions are usually cracked to maximise overall fuel yields.

In Australia the most likely location of the Fischer-Tropsch plant would be in north-western Western Australia. In such case the upstream emissions would arise from natural gas recovery and processing, syngas and Fischer-Tropsch processes, upgrading plant, transportation to the major cities and the distribution to retail outlets.

A whole range of fuels can be produced from natural gas by partial oxidation to synthesis gas (a mixture of H_2 and CO) and the subsequent conversion of this gas.

Shell's SMDS (Shell Middle Distillate synthesis) plant in Bintulu is an example. In this plant naphtha, kerosene and Fischer Tropsch Diesel (FTD) are produced as well as a number of specialized products. With a syngas yield of 95%, syngas conversion of 96%, liquid selectivity of over 90% and a refining and separation loss of 2%, the carbon efficiency of Fischer Tropsch Diesel production is higher than 80% (Seden and Punt, 1999). The energy efficiency of this part of the plant is 63%. Energy use and CO_2 emissions are presented in

Table 3.1. The quoted carbon and thermal efficiencies in this paragraph refer to the next generation SMDS plants.

The syngas used to produce methanol is mainly produced by steam reforming of natural gas. Methanex gives an efficiency of 67% for auto-thermal reforming based on lower heating value (Methanex, 1999)

Assuming that the liquid fuels are mainly transported by road tanker, the transport efficiency is a function of the lower heating value of the fuel. These transport efficiencies are given in Table 3.1.

As noted in Table 1.1 of Part 1 of this report, the upstream emissions are based on the work of Wang and Huang (1999), with the assumption that the GTL facility will be located at the northwest shelf. The tailpipe emissions are those of Norton et al. (1998).

Table 3.1a
Energy use and GHG emissions output from the GREET model (Louis, 2001, Wang 1999).

	Energy efficiency	Energy use (MJ/MJ)	GHG (g/MJ)
FTD production	63	0.600	25.2
FTD transport	99.5	0.006	0.4

Table 3.1b
Energy use and GHG emissions output from the GREET model (Wang 1999) as applied in the upstream analysis.

		Unit	Value	Formulae/ Source
A	Energy efficiency of process	% by energy	66.0%	Wang (1999)
B	FTD Energy Content	MJ/kg	41.3	Fuel report
C	Total Feedstock	MJ	62.6	B/A
D	Energy use in process	MJ	21.29	C-B
E	Energy content methane	MJ/kg	50	
F	NG input	kg	1.25	C/E
G	Carbon in NG	kg	0.939	F*12/16
H	Carbon efficiency	% by weight	76%	Wang (1999)
I	Carbon to FTD	kg	0.71	G*H
J	Carbon Emitted	kg	0.225	G-I
K	Emitted Carbon as CO2	kg	0.826	J*44/12
L	CO2 emission factor per MJ NG used	kg CO2/MJ	0.0544	NGGI 2000
M	NG consumed MJ	MJ	15.19	L/M
N	Hydrogen Consumed by balance	MJ	6.10	D-M
O	Hydrogen Energy content	MJ/kg	120	
P	H Mass	kg	0.051	N/O
Q	gas required for H content	kg	0.203	P*16/4
R	gas required for energy	kg	0.30	M/E
S	Gas used purely as feedstock	kg	0.75	F-(Q+R)

Energy consumption for the production of FTD was taken from Wang (1999), based on an energy efficiency figure for production, of 66%. This figure includes allowance for energy credits granted through co-generation of electricity from excess heat produced in the Fischer-Tropsch process. However the energy used in FTD production comes both from natural gas – (considered here as methane because all other products are assumed to be stripped off) and from hydrogen produced in the gas shift reaction used as part of the FTD process. It is important to estimate how much energy comes from each source as the hydrogen combustion does not produce CO_2. An estimate of the split between energy supplied by CH_4 and that supplied by H_2 is given below based on Wang's data claiming a 66% energy efficiency and a 77% carbon efficiency. The net result is 15.2 MJ being sourced from gas and 6.1MJ being from hydrogen produced.

3.2.2 Tailpipe emissions

Table 3.2 provides results for light vehicles, in particular Mercedes A-class vehicles. The diesel version of the A-Class (1.7L) uses 4.9 litre of diesel for 100 km on the same drive-cycle or 1.89 MJ/km. It is assumed that the other compression ignition vehicles (running on Fischer Tropsch Diesel or di-methylether) use the same amount of energy.

Greenhouse gas emissions are calculated from the calorific value of the fuel used and its carbon content. Only the natural gas vehicle emits a significant amount of methane, but even this is only equivalent to 0.6 grams of CO_2 per km. Energy use and greenhouse gas emissions from internal combustion engine vehicles are given in Table 3.2.

Table 3.2.
Energy use by and GHG emissions from internal combustion engine vehicles

ICE vehicle	Energy (MJ/km)	GHG (g/km)
Petrol	2.42	172
Natural gas	2.42	128
Diesel	1.89	131
Fischer Tropsch Diesel	1.89	128
Hydrogen	1.89	0

Source: Louis (2001)

Lom (pers. comm.) provided data on the relative performance of biodiesel and advanced GTL diesel. These data are reproduced in Table 3.3.

Table 3.3
Average results with biodiesel and GTL fuel on standard tests

Test	Euro R49 Biodiesel	Transient GTL
CO	-12%	-40%
HC	-40%	-40%
NOx	+20%	0
PM	+13%	-30%
Smoke	-70%	-50%
Fuel conservation	+15%	+10%
Power	-10%	-8%

Emissions from FTdiesel fuel have been examined by Schaberg et al. (1997), by Norton et al. (1998) and more recently by Durbin et al. (2000) who looked only at light commercial vehicles (pickup trucks). The results from Norton et al. (1998) are given in Table 3.4 for the engine tests and in Table 3.5 for the chassis dynamometer tests. As is evident in Tables 3.2 and 3.5 there are large differences between emissions from light vehicles and heavy trucks when expressed on a per distance basis. Most emissions increase roughly linearly with fuel consumption, though NOx appears to increase exponentially with load.

Table 3.4
Exhaust emissions from hot-start FTP engine tests in g/bhp-h

	HC	CO	NOx	PM	CO_2
Conventional US #2 Diesel	0.346	1.584	5.373	0.120	643.75
California #2 Diesel	0.274	1.091	4.893	0.109	615.85
FT Diesel	0.198	0.968	4.607	0.104	611.49

Table 3.5
Exhaust emissions from the WVU 5-mile cycle in g/mile (Truck 2016)

	HC	CO	NOx	PM	CO_2	mpg*	BTU/mile
California #2 Diesel	0.89	4.26	12.8	0.59	1755	5.67	22541
FT Diesel for heavy vehicle (Norton, 1998)	0.50	3.21	11.2	0.48	1634	5.63	21947
FT Diesel for light vehicle (Wang, 1999)	0.05	2.76	0.06	0.03	268	36	3118

* miles per liquid gallon (not corrected for energy content)

The values of Table 3.5 were used in the quantitative calculations.

3.3 *Results*

The results given in this section compare the use of Fischer-Tropsch diesel and low sulfur diesel in heavy vehicles.

3.3.1 Emissions per unit energy

Table 3.6
Exbodied emissions per MJ of FT diesel

Full Lifecycle	Units	LS diesel	FT diesel
Greenhouse	kg CO_2	0.0858	0.0975
NMHC total	g HC	0.140	0.093
NMHC urban	g HC	0.111	0.050
NOx total	g NOx	1.044	0.996
NOx urban	g NOx	0.987	0.848
CO total	g CO	0.253	0.225
CO urban	g CO	0.242	0.192
PM10 total	mg PM10	40.7	25.5
PM10 urban	mg PM10	39.3	23.5
Energy Embodied	MJ LHV	1.18	1.78

Table 3.7
Urban and total upstream emissions per MJ for FT diesel

Units	Units	LS diesel	FT diesel
Greenhouse	kg CO_2	0.0191	0.0336
NMHC total	g HC	0.0565	0.0443
NMHC urban	g HC	0.027	0.001
NOx total	g NOx	0.100	0.153
NOx urban	g NOx	0.043	0.005
CO total	g CO	0.023	0.035
CO urban	g CO	0.012	0.001
PM10 total	mg PM10	5.42	2.11
PM10 urban	mg PM10	4	0.0763
Energy Embodied	MJ LHV	1.18	1.78

Table 3.8
Urban and total tailpipe emissions per MJ from FT diesel

Combustion	Units	LS diesel	FTdiesel
Greenhouse	kg CO_2	0.067	0.064
NMHC total	g HC	0.084	0.049
NMHC urban	g HC	0.084	0.049
NOx total	g NOx	0.944	0.843
NOx urban	g NOx	0.944	0.843
CO total	g CO	0.230	0.191
CO urban	g CO	0.230	0.191
PM10 total	mg PM10	35.26	23.43
PM10 urban	mg PM10	35.26	23.43
Energy Embodied	MJ LHV	0	0

Table 3.9
Summary of life cycle emissions per MJ from FT diesel

		LS diesel	FTdiesel
Greenhouse kg	Precombustion	0.0191	0.0336
Greenhouse kg	Combustion	0.0667	0.0639
NMHC total g	Precombustion	0.0565	0.0443
NMHC total g	Combustion	0.0835	0.0491
NMHC urban g	Precombustion	0.0271	0.0009
NMHC urban g	Combustion	0.0835	0.0491
NOx total g	Precombustion	0.1000	0.1530
NOx total g	Combustion	0.944	0.843
NOx urban g	Precombustion	0.043	0.005
NOx urban g	Combustion	0.944	0.843
CO total g	Precombustion	0.0225	0.0346
CO total g	Combustion	0.2301	0.1907
CO urban g	Precombustion	0.0123	0.0010
CO urban g	Combustion	0.2301	0.1907
PM10 total mg	Precombustion	5.42	2.11
PM10 total mg	Combustion	35.26	23.43
PM10 urban mg	Precombustion	4.00	0.08
PM10 urban mg	Combustion	35.26	23.43
Energy Embodied MJ	Precombustion	1.18	1.78

3.4 Emissions per unit distance travelled

Table 3.10
Exbodied emissions per km from FT diesel

Full Lifecycle	Units	LS diesel	FTdiesel
Greenhouse	kg CO_2	0.9250	0.9926
NMHC total	g HC	1.509	0.940
NMHC urban	g HC	1.192	0.524
NOx total	g NOx	11.250	10.305
NOx urban	g NOx	10.638	8.896
CO total	g CO	2.723	2.333
CO urban	g CO	2.612	2.010
PM10 total	mg PM10	438.4	266.1
PM10 urban	mg PM10	423.1	246.6
Energy Embodied	MJ LHV	12.7	17.10

Table 3.11
Urban and total upstream emissions per km for FT diesel

Precombustion	Units	LS diesel	FT diesel
Greenhouse	kg CO_2	0.2060	0.3220
NMHC total	g HC	0.609	0.425
NMHC urban	g HC	0.292	0.009
NOx total	g NOx	1.080	1.460
NOx urban	g NOx	0.468	0.051
CO total	g CO	0.243	0.332
CO urban	g CO	0.132	0.009
PM10 total	mg PM10	58.4	20.3
PM10 urban	mg PM10	43.1	0.732
Energy Embodied	MJ LHV	12.7	17.1

Table 3.12
Urban and total tailpipe emissions per km from FT diesel

Combustion	Units	LS diesel	FT diesel
Greenhouse	kg CO_2	0.719	0.671
NMHC total	g HC	0.900	0.515
NMHC urban	g HC	0.900	0.515
NOx total	g NOx	10.170	8.845
NOx urban	g NOx	10.170	8.845
CO total	g CO	2.480	2.001
CO urban	g CO	2.480	2.001
PM10 total	mg PM10	380.00	245.86
PM10 urban	mg PM10	380.00	245.86
Energy Embodied	MJ LHV	0	0

Table 3.13
Summary of life cycle emissions per km from FT diesel

		LS diesel	FT diesel
Greenhouse kg	Precombustion	0.2060	0.3220
Greenhouse kg	Combustion	0.7190	0.6706
NMHC total g	Precombustion	0.6090	0.4250
NMHC total g	Combustion	0.9000	0.5153
NMHC urban g	Precombustion	0.2920	0.0089
NMHC urban g	Combustion	0.9000	0.5153
NOx total g	Precombustion	1.0800	1.4600
NOx total g	Combustion	10.170	8.845
NOx urban g	Precombustion	0.468	0.051
NOx urban g	Combustion	10.170	8.845
CO total g	Precombustion	0.2430	0.3320
CO total g	Combustion	2.4800	2.0006
CO urban g	Precombustion	0.1320	0.0094
CO urban g	Combustion	2.4800	2.0006
PM10 total mg	Precombustion	58.40	20.30
PM10 total mg	Combustion	380.00	245.85
PM10 urban mg	Precombustion	43.10	0.73
PM10 urban mg	Combustion	380.00	245.85
Energy Embodied MJ	Precombustion	12.70	17.10

3.4.1 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 3.14.

Table 3.14
Estimated one standard deviation uncertainties (in percent) for Fischer-Tropf diesel emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	9	11
NMHC	34	50	17
NOx	29	30	27
CO	111	144	78
PM10	45	39	50

Part 2 Details of Fuels

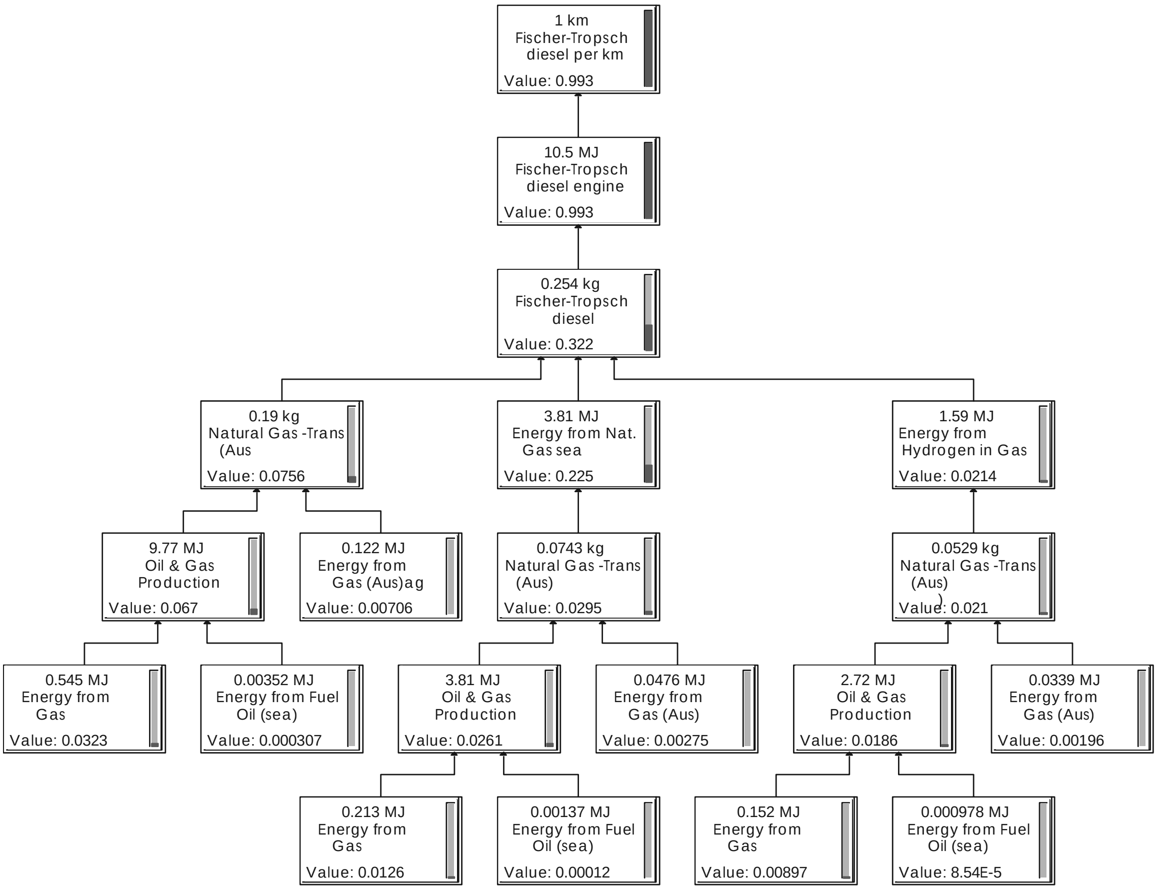

Figure 3.3
Exbodied greenhouse gases emissions (kg CO_2eq) from FTP diesel production and processing and use in vehicle

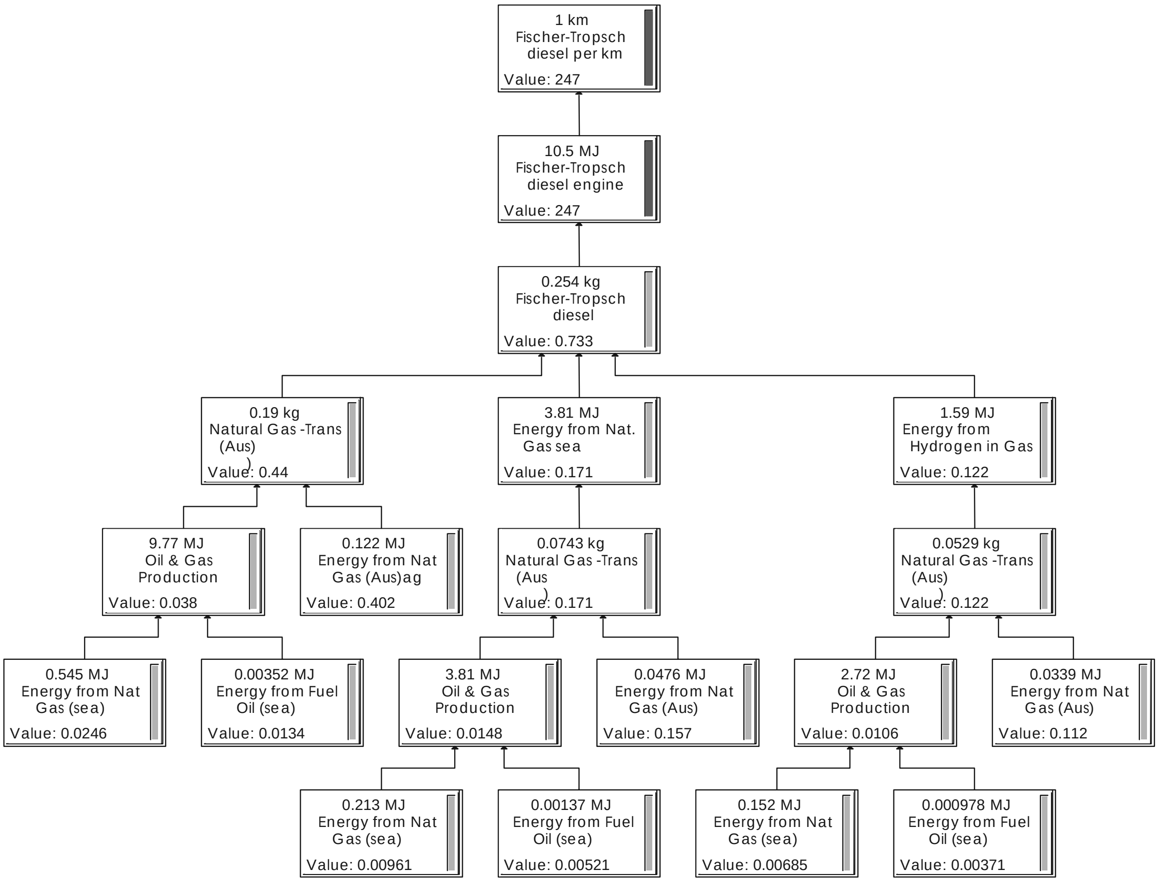

Figure 3.4
Exbodied particulate matter (mg - urban) from FTP diesel production and processing and use in vehicle

3.5 Viability and functionality

FT diesel has the same viability and functionality as diesel fuel. The fuel properties of the California diesel and the FT diesel (when converted from BTU/gal) used in the testing by Norton et al. (1998), as shown in Table 4 are given in Table 3.15.

Table 3.15
FT diesel fuel properties (MJ/L)

	California #2 Diesel	**FT Diesel**
Gross Heat of Combustion (HHV)	37.92	36.86
Nett Heat of Combustion (LHV)	35.56	34.36

SasolChevron (Goede, pers. comm.) point out that FT fuels:

- are already in use and production in South Africa where approximately 190,000 barrels per day are produced from either natural gas or coal gas;
- comply with South African Bureau of Standards (SABS 342-1998) specification for automotive diesel fuels to which the major automotive companies are co-signatories;
- are used by Ford South Africa as the first fuel with which to fill the tanks of new trucks;
- have similar refuelling and operational ranges to diesel;
- are compatible with existing diesel distribution and storage infrastructure as well as old, existing and future engine technologies (Schaberg et al., 1997);

- enhance engine durability and prolong service intervals as a result of their low sulfur content (Weiss et al., 1987).

Some of these properties are shared with all ultra low sulfur diesel fuels. For example, very low sulfur is needed for future generations of catalyst systems.

3.6 Health Issues

FT diesel is an extremely low sulfur diesel, with sulfur content less than 10ppm. The health benefits, when compared to the low sulfur diesel reference fuel will be at least those of ultra low sulfur diesel (ULS).

A web search using “citydiesel” and “health” as search terms indicated that Finnish studies claim that there are 20% reductions in aromatics from the tailpipe of the vehicles using such extremely low sulfur diesel fuels.

In addition, material provided by SasolChevron notes that the total aromatic content of Sasol GTL fuel is approximately 0.4% by mass with PAH being less than 0.05%. The comparable low sulfur diesel values are 32.2% aromatics and 2.5% to 10% PAH. These order-of-magnitude reductions result in significant lowering of potential adverse health effects from emissions associated with FT diesel (Schaberg et al., 1997).

3.6.1 Production and transport

Particulate Matter
The LCA estimate for FT Diesel urban precombustion (truck) PM10 emissions of 1 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air Toxics
The LCA estimate for FT diesel urban precombustion (truck) NMHC emissions of 0.011 g/km is substantially less than the LSD estimate of 0.292 g/km.
The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxics emissions from upstream activities.

3.7 Use

3.7.1 Particulate matter

The LCA estimate for FT Diesel combustion (truck) PM10 emissions of 246 mg/km is less than the LSD estimate of 380 mg/km.

3.7.2 Air toxics

The LCA estimate for FT Diesel combustion (truck) NMHC emissions of 0.515 g/km is less than LSD estimate of 0.900 g/km.

3.7.3 Summary

FT Diesel upstream emissions of both particles and NMHC are substantially less than LSD.
FT Diesel tailpipe emissions of both particles and NMHC are less than LSD.
No comparative emissions data for FT Diesel and LSD has been identified for air toxics.

3.8 OHS Issues

The OHS issues in the lifecycle of FT Diesel are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with FT Diesel compared with LSD, no OHS issues unique to the production and distribution of FT Diesel have been identified.

3.9 Vapour Pressure Issues

No information was identified on vapour pressure issues associated with FT Diesel.

3.10 Summary

The advantages of FT Diesel are:

- FT Diesel contains virtually no sulfur or aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The absence of sulfur means that oxidation catalysts and particulate traps will operate at maximum efficiency.
- The existing diesel infrastructure can be used, unchanged, for Fischer-Tropsch Diesel.
- FT Diesel can be used in existing diesel engines.
- Diesel is one of the safest of the automotive fuels.
- An FT plant does not produce any of the less desirable co-products from a refinery, such as heavy fuel oil or coke.
- Provided an FT plant uses an oxygen feed, it produces a pure CO_2 stream that provides an option for the collection and sequestration of CO_2.

The disadvantages of Fischer-Tropsch diesel are:

- Diesel exhaust (including FT Diesel exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, FT Diesel produces more exbodied greenhouse gases than any of the conventional or alternative fuels studied in this report.

3.11 Environmental Impact and Benefits

Greene (1999) comprehensively reviews the environmental issues involved with GTL fuels. The environmental impacts are the same as those for diesel fuel, with the benefit of lower air pollutant emissions and increased resource security through a lowered dependence on imported oil.

An FTD plant does not produce undesirable co-products, unlike a refinery, which produces heavy fuel oil and coke.

3.12 ADR Compliance

Ultra low sulfur fuel is being introduced specifically to enable Euro4 fuel specifications to be met. The ADR have been based on this fuel. There should thus be no potential for an even lower sulfur fuel such as FT Diesel to compromise vehicles’ compliance with gazetted ADR standards.

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4. Biodiesel

4.1. *Biodiesel from Vegetable Oils*

Diesel engines initially perform to much the same standard with pure vegetable oil as with diesel. In the past pure vegetable oils have been mainly used in tractors on farms. Pure vegetable oils create problems in turbocharged direct injection engines with charge air coolers, such as those used in trucks.

Table 4.1 compares some of the physical and chemical properties of diesel, canola oil and methyl esters. Vegetable oils have higher density than diesel, but lower energy content (gross calorific value). Vegetable oils have a lower carbon content than diesel, which means lower CO_2 emissions per litre of fuel burnt. CO_2 emissions per kilometre travelled may not be lower, however, due to the lower energy content of the vegetable oils and a higher proportion of multi bonded carbon compounds. The major difference in physical characteristics between canola and diesel is in the viscosity. Canola is more than 12 times as viscous as diesel at 20°C, and remains more than six times as viscous even after heating to 80°C.

Table 4.1
Comparison of typical properties of diesel, canola oil, commercial US biodiesel, and various methyl esters.

	Diesel	**Canola**	**Biodiesel (FAMAE)**	**Palm oil methyl ester**	**Soy methyl ester**	**Sunflower methyl ester**	**Tallow methyl ester**
Density (kg/L) at 15.5°C	0.835	0.922	0.88	0.880	0.884	0.880	0.877
Gross calorific value (MJ/L)	38.3	36.9	33.3	37.8	39.8	38.1	39.9
Viscosity (mm^2/s @ 37.8°C)	3.86	37	4.7	5.7	4.08	4.6	4.1
Cetane number	51 to 58		> 40	62	46	49	58

Source: Adapted from Table 6.1 of BTCE (1994), from www.afdc.doe.gov, and from Clements (1996).
FAMAE: Fatty Acid Mono Alkyl Ester

These high viscosity levels create problems for the use of canola, or other pure vegetable oils, as an unmodified fuel. The flow of the fuel from tank to engine is impeded, which can result in decreased engine power. Fuel filter blockages may also occur. The multi-bonded compounds pyrolyse more readily and engines can suffer coking of the combustion chamber and injector nozzles, and gumming, and hence sticking, of the piston rings. A progressive decline in power results. If left unchecked, dilution of the crankcase oil can lead to lubrication breakdown. Long-term tests have verified that there is a build-up of carbon deposits in the injection nozzles and cylinder heads.

The viscosity problem can be mitigated by preheating the oil and using larger fuel lines, by blending diesel and vegetable oils, or by chemical modification (i.e. producing biodiesel). Apart from the viscosity difficulties, vegetable oils may result in starting difficulties due to a high temperature being required before the oil will give off ignitable vapours. They also have a relatively slow burn rate as a result of the low cetane rating, which makes vegetable oils unsuitable for high speed engines.

4.2. *Biodiesel*

Biodiesel is a generic name for fuels obtained by transesterification of a vegetable oil. This produces a fuel with very similar combustion properties to pure diesel, but with lower viscosity. Often biodiesel refers to rapeseed oil methylester (RME), the main European biodiesel. Esterified soybean oil is the main United States source of such fuel, called Soy diesel. Figure 4.1 depicts a flow chart of the esterification process.

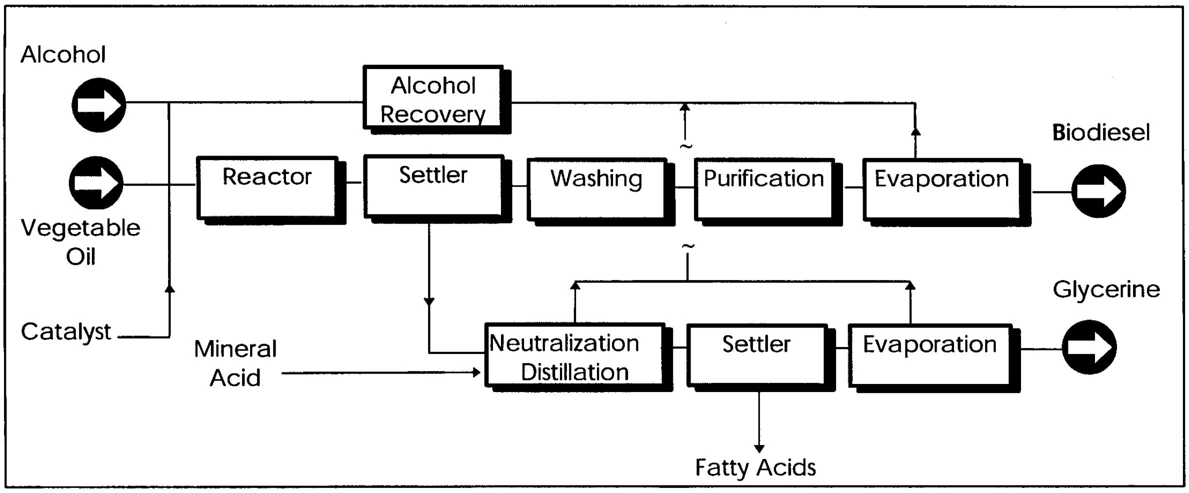


Figure 4.1
Flowchart of the process of esterification to create biodiesel fuel
Source: National Biodiesel Board production factsheet

Biodiesel can be used in a diesel engine without modification. Mittelbach (1998) quotes a cetane number of 48 for rapeseed methyl ester but notes that this can be increased to 59 if the biodiesel is made from the ethyl esters of tropical oilseeds. Mann (1998) claims a cetane number of 56 for soydiesel. The fuel consumption of biodiesel per kilometre travelled is similar to that for diesel when biodiesel is used as a diesel blend. Biodiesel has a lower energy content than diesel that leads to increased fuel consumption when pure biodiesel is used (Taberski et al., 1999).

The greenhouse gas emissions arising from the process depicted in Figure 4.1 depend on the amount of fossil fuel involved in the production of the alcohol. If methanol is used then this process is described by the equation.

$$\underset{\text{(Triglyceride)}}{C_3H_5(OOCR)_3} + \underset{\text{(Methanol)}}{3CH_3OH} \rightarrow \underset{\text{(Methylester)}}{3RCOOCH_3} + \underset{\text{(Glycerine)}}{C_3H_5(OH)_3}$$

The term “triglyceride” in the equation may be either vegetable oil or tallow. From a chemical point of view, the differences between various plant and animal derived fats are due to the structural variations of fatty acids contained in fat molecules.

In most fats, the length of the fatty acid carbon chain ranges between C16 and C18. There are also differences in the degree of saturation (number and position of double bonds) in acid molecules. Saturation is the major factor determining physical properties of fats. Highly unsaturated vegetable oils are low viscosity liquids, while fully saturated animal fats are solid at ambient temperature.

From the point of view of the transesterification process itself, these differences in molecular structure are insignificant in terms of process parameters or energy demand. The greenhouse gas emissions arising from the process depicted in Figure 4.1 depend mostly on the amount of fossil fuel involved in the production of the alcohol as given by Sheehan et al. (1998: p. 147), who estimate that 5% (by mass) of the carbon emissions are fossil-fuel carbon.

For example, if methanol is used, overall emissions will be higher because current production of methanol involves solely fossil-fuel feedstocks such as natural gas or coal. By contrast, if the use of ethanol produced from renewable resources (biomass) using bioprocesses is contemplated, greenhouse emissions will be lower. Methanol can be produced by the gasification of biomass but this is currently not done.

Another source of differences in life-cycle emissions of biodiesel arises at the stage of oil and tallow production. In the case of oil-seed crops, there needs to be accounting for energy and raw materials inputs into fertiliser production, land cultivation, materials transportation, harvesting and oil extraction. Similarly, when tallow is used as a feedstock, energy expended in farming activities needs to be accounted for. In both cases appropriate allocation procedures for multiple product streams need to be observed.

Table 4.2
Comparison of different national standards for biodiesel

		Austria	**Czech Republic**	**France**	**Germany**	**Italy**	**Sweden**	**USA**
Standard / Specification		ON C1191	CSN 65 6507	Journal Officiel	DIN V 51606	UNI 10635	SS 155436	ASTM PS121-99
Date		July 1997	Sep 1998	Sep 1997	Sep 1997	April 1997	Nov 1996	July 1999
Application		FAME	RME	VOME	FAME	VOME	VOME	FAMAE
Density 15°C	g/cm³	0.85 - 0.89	0.87 - 0.89	0.87 - 0.90	0.875 - 0.90	0.86 -0.90	0.87 - 0.90	-
Viscos. 40°C	mm²/s	3.5-5.0	3.5 - 5.0	3.5-5.0	3.5-5.0	3.5-5.0	3.5-5.0	1.9-6.0
Distillat. 95%	°C	-	-	≤ 360	-	≤ 360	-	-
Flashpoint	°C	≥100	≥110	≥ 100	≥ 110	≥ 100	≥ 100	≥100
CFPP	°C	0/-15	-5	-	0/-10/-20	-	-5	-
Pourpoint	°C	-	-	≤ -10	-	≤ 0/≤-15	-	-
Sulfur	% mass	≤ 0.02	≤ 0.02	-	≤ 0.01	≤ 0.01	≤ 0.001	≤ 0.05
CCR 100%	% mass	≤ 0.05	≤ 0.05		≤ 0.05			≤ 0.05
10% dist. resid.	% mass			≤ 0.3		≤ 0.5	-	
Sulfated ash	% mass	≤ 0.02	≤ 0.02	-	≤ 0.03	-	-	≤ 0.02
(Oxid) Ash	% mass	-	-	-	-	≤ 0.01	≤ 0.01	-
Water	mg/kg	-	≤500	≤ 200	≤ 300	≤ 700	≤ 300	≤0.05%
Total contam.	mg/kg	-	≤ 24	-	≤ 20	-	≤ 20	-
Cu-Corros. 3h/50°C		-	1	-	1	-	-	≤ No.3
Cetane No.	-	≥ 49	≥ 48	≥ 49	≥ 49	-	≥ 48	≥ 40
Neutral. No.	mgKOH/g	≤ 0.8	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.6	≤ 0.8
Methanol	% mass	≤ 0.20	-	≤ 0.1	≤ 0.3	≤ 0.2	≤ 0.2	-
Ester content	% mass	-	-	≥ 96.5	-	≥ 98	≥ 98	-
Monoglycides	% mass	-	-	≤ 0.8	≤ 0.8	≤ 0.8	≤ 0.8	-
Diglyceride	% mass	-	-	≤ 0.2	≤ 0.4	≤ 0.2	≤ 0.1	-
Triglyceride	% mass	-	-	≤ 0.2	≤ 0.4	≤ 0.1	≤ 0.1	-
Free glycerol	% mass	≤ 0.02	≤ 0.02	≤ 0.02	≤ 0.02	≤ 0.05	≤ 0.02	≤ 0.02
Total glycerol	% mass	≤ 0.24	≤ 0.24	≤ 0.25	≤ 0.25	-	-	≤ 0.24
Iodine No.		≤ 120	-	≤ 115	≤ 115	-	≤ 125	-
C18:3 and high. unsat.acids	%mass	≤ 15	-	-	-	-	-	-
Phosphor	mg/kg	≤ 20	≤ 20	≤ 10	≤ 10	≤ 10	≤ 10	-
Alkalinity	mg/kg	-	≤ 10	≤ 5	≤ 5	-	≤ 10	-

RME: Rapeseed oil methyl ester
FAME: Fatty acid methyl ester
VOME: Vegetable oil methyl ester
FAMAE: Fatty acid mono alkyl ester

4.3. National Standardisation of Biodiesel

The introduction of biodiesel as a fuel for diesel engines called for the development of standards in the respective countries. Thus, a working group in Austria in 1990 was instructed to prepare a standard for rape oil methyl ester. Currently, standards or specifications for biodiesel are available in Austria, the Czech Republic, France, Germany, Italy, Sweden, and the United States. Table 4.2 shows a summary of currently valid national standards (Prankl and Woergetter, 1999). Environment Australia plans to develop standards for biodiesel under the *Fuel Quality Standards Act 2000.*

In Europe biodiesel is predominantly produced from rapeseed oil, and most information and data available deals with the practical experience gained in the use of rapeseed oil methyl ester (RME). In Austria and the Czech Republic standards for RME have been developed. In France, Italy and Sweden the specifications for biodiesel deal with plant oil used as a raw material. In Austria and Germany general standards for fatty acid methyl ester have been developed. The United States define biodiesel as “mono-alkyl esters of long chain fatty acids derived from vegetable oils and animal fats”. However, the choice in raw material is limited considerably in the standards because of the selection of limiting values. By the year 2002 it is expected that there will be a European wide standard for biodiesel.

4.4. Tailpipe Emissions

The extensive use of biodiesel fuels in the United States and Europe means that data is available on their emission characteristics during operational performance. Such data from the United States and from Europe was summarised by Beer et al. (2000). This section of the report reviews recent results, and some of the relevant older results. The next section compares the different studies.

Due to the absence of sulfur and the presence of oxygen in biodiesel, one would expect theoretically lower particle emissions. Recent results by Sharp et al. (2000a, b) indicate that modern American engines are now showing lowered particle emissions. Previous work by Motta, et al. (1996) using biodiesel in an earlier generation of engines installed in buses, indicated higher particle emissions. However, the high oxygen content means that the use of pure biodiesel generally results in a measurable loss of engine power and an increase in fuel consumption.

Table 4.3
Engine dynamometer results (g/kWh) of emissions from a 20% blend of various biodiesel with diesel

	CME20/Diesel	CME20/LSD	SME20/LSD
Total PM	0.32	0.34	0.36
Total HC	0.49	0.59	0.64
NOx	7.87	7.44	6.31
CO	1.40	1.61	1.50
CO_2	875	877	924

Source: Spataru and Romig (1995) CME20 = 20% Canola methylester; SME20 = 20% Soy methylester

Spataru and Romig (1995) examined emissions from a DCC 6V92TA motor on an engine dynamometer, when both soy and canola methyl esters were used in blends with ordinary diesel and low sulfur diesel (California diesel). Their results are given in Table 4.3.

On the basis of the results in Table 4.3, it appears that biodiesel made from canola emits less greenhouse gases than biodiesel made from soy.

Most results and analyses that we have been able to find relate to methyl esters. Taberski et al. (1999) looked at the biodiesel emissions when using rapeseed ethyl ester (REE) blends in a 1995 Dodge 2500 four-wheel-drive pickup truck with a Cummins B 5.9 litre turbocharged direct injection diesel engine. They obtained results in 1995 and in 1998 with and without a catalytic converter. Table 4.4 and Table 4.5 present their results as the ratio of the observed emissions to the ratio obtained using D2 diesel, which is United States low sulfur diesel containing 450 ppm sulfur. Both the ratios obtained in the 1995 tests and the ratios obtained in the 1998 test are given.

Table 4.4
Range of ratios between emissions using diesel and ethyl ester biodiesel (no catalytic converter)

	HC	CO	NOx	CO_2	PM
REE20%	0.782-0.834	0.723-0.824	0.925-0.972	0.966-1.006	1.007-1.059
REE50%	0.565-0.642	0.648-0.652	0.926-0.971	1.007-1.026	1.352-1.338
REE100%	0.369-0.380	0.553-0.652	0.876-0.918	0.978-1.006	1.348-1.420

Table 4.5
Range of ratios between emissions using diesel and ethyl ester biodiesel (with catalytic converter)

	HC	CO	NOx	CO_2	PM
REE20%	0.834-0.922	0.822-0.841	0.950-0.964	1.007-1.012	1.283-1.278
REE50%	0.628-0.693	0.655-0.692	0.913-0.932	0.986-1.005	1.257-1.403
REE100%	0.364-0.385	0.534-0.668	0.905-0.919	1.000-1.021	1.109-1.255

In 1998 the Southwest Research Institute, on behalf of the United States National Biodiesel Board, generated data for submission to the USEPA in order to comply with Tier 1 requirements under section 211(b) of the Clean Air Act. The data (Sharp, 1998) was based on regulated and unregulated emissions from a new 1997 Cummins N14 engine. The testing was carried out over the heavy-duty transient Federal Test Procedure. The biodiesel used was Soy methyl ester, with a cetane number of 51.2. The reference fuel was number 2 diesel with a cetane number of 43.3, and a sulfur content of 476 ppm. These results were used in the LCA to characterise biodiesel tailpipe emissions.

The results from the National Biodiesel Board/USEPA Tier 1 Health and Environmental Effects Testing for Biodiesel (Sharp, 1998; Sharp et al., 2000a) are summarised in section 4.13.

4.4.1 Air toxics

The United States National Biodiesels Board summarised studies on the air toxics emitted during biodiesel combustion, compared to diesel combustion. These results, given on the web site (http://www.biodiesel.org/fleets/summary.shtml#attributes) during 1999, are reproduced in Table 4.6.

Table 4.6
Gaseous PAH levels (µg/cycle) of diesel fuel and a 50% biodiesel diesel blend.

	Diesel	50% Biodiesel
Naphthalene	331,654	384
Methyl-2 Naphthalene	10,289	329
Fluorene	1,864	368
Anthracene	4,301	873

Particulate matter and unburned hydrocarbon emissions

Chang and van Gerpen (1998) studied a John Deere model 4276T, 4 cylinder, 4 stroke, turbocharged, D1 diesel engine under dynamometer testing with a double dilution tunnel system. As fuels they used D2 diesel and biodiesel.

They concluded that under steady state testing (100% of maximum torque at 1400 rpm; 20% of maximum torque at 1400 rpm) the experimental results confirmed that biodiesel produced a higher soluble organic fraction (SOF) in its total particulate matter than diesel fuel under virtually all engine operating conditions. The SOF decreased with increasing particle filter temperature at constant dilution ratio and with increasing dilution ratio at constant filter temperature. Adsorption of vapour phase biodiesel on the carbon particle surface is the primary source of the SOF in the total particulate matter. We suspect that discrepancies in reported particulate matter results, discussed below, may result from different methods of reporting these SOF fractions.

4.5. Comparison of Tailpipe Emissions

Beer et al. (2000) points out that there are discrepancies between biodiesel emission results emanating from Europe and from the United States. In addition, during liaison meetings with stakeholders, particular concern was expressed that the findings by Beer et al. (2000) indicated greater tailpipe emissions of particulate matter from biodiesel than from diesel.

In particular, our attention was drawn to the results from the first phase of emissions testing programs (Tier I testing) on biodiesel undertaken on behalf of the National Biodiesel Board under USEPA regulations governing the introduction of new fuels and fuel additives (Sharp, 1998), and we used these data to characterise combustion emissions in the quantitative life-cycle analysis. The exhaust emissions of particulate matter in this study were found to be 30% lower than overall particulate matter emissions from diesel. Exhaust emissions of the insoluble portions of the particulate matter emissions were reduced by 80% for biodiesel compared to diesel.

To further examine this issue, Table 4.7 summarises the results of recent studies that compare the tailpipe emissions of biodiesel (BD100) to low sulfur diesel, generally United States D2 diesel. The only consistent finding is that biodiesel does not produce more tailpipe emissions of hydrocarbons than diesel fuel. For all the other pollutants in the table, some studies report an increase, whereas other studies report a decrease.

Table 4.7
Comparison between emissions from biodiesel (BD100) and low sulfur diesel

Vehicle		CO	NOx	THC	PM	Source
Buses	US Fleet	+	+	0	+	Beer et al. Table 2.10
Trucks	US Fleet	+	+	no data	+	Beer et al. Table 2.11
Cummins N14 Engine		-	+	=	-	Sharp 1998 Table 3
Dodge LCV	with catalyst	-	-	=	+	Taberski et al. 1999
Dodge LCV	with catalyst	-	0	=	-	Durbin et al. 2000
Dodge LCV	without catalyst	-	-	=	+	Taberski et al. 1999
Dodge LCV	without catalyst	+	+	-	+	Durbin et al. 2000
Ford LCV	with catalyst	-	+	-	+	Durbin et al. 2000
Ford LCV	without catalyst	-	0	=	+	Durbin et al. 2000
Composite	European	-	+	-	-	IEA/AFIS 1999
Composite	Swedish LDV	=	0	=	-	Arcoumanis 2000 Table 5.2
Composite	Swedish HDV	-	0	=	0	Arcoumanis 2000 Table 5.3a

Symbols: ++ biodiesel more than double diesel emissions, + more, 0 within 10%, - less, = biodiesel less than half diesel emissions.

4.5.1 Hydrocarbons and carbon monoxide

Hydrocarbon emissions are mostly the result of flame quenching in an internal combustion engine. There is a narrow quench zone near the cooled cylinder walls that makes the flame go out and the hydrocarbons are not burned. CO is partially combusted fuel. Because of this, HC and CO are typically very high on cold start due to colder engine parts quenching the flame and preventing complete combustion. Biodiesel will reduce both HC and CO compared to diesel in the same engine, under the same conditions (Taberski et al., 1999).

4.5.2 Oxides of nitrogen

The NOx emissions behaviour of biodiesel in unmodified diesel engines varies in the literature, as evidenced by Table 4.7. This variability may be due to individual variables in the engines themselves. Gonzalez-Gomez et al. (2000) examined the emissions from esterified waste cooking oil and found that NOx levels were higher (than those of diesel) at all vehicle speeds.

4.5.3 Particulate matter

Taberski et al. (1999) suggest that whether one observes reductions in particulate matter when biodiesel is used in a diesel engine depends on the trade-off between a reduction in carbon soot and an increase in the soluble organic fraction. An exhaust catalyst typically reduces the soluble organic fraction – yet despite this we still note that there are studies on vehicles with such catalysts that report higher particle emissions from biodiesel than from diesel.

4.6. Upstream Emissions of Canola and Rapeseed

4.6.1 Background

Canola is a member of the *Brassica* Family, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed, with less crucic acid and glucosinolates than rapeseed. Grown for its seed, the seed is crushed for the oil contained within. After the oil is extracted, the by-product is a protein rich meal used by the intensive livestock industry.

In the 1990s, canola production increased dramatically due to new disease resistant varieties (Black Leg Resistance) and strong oilseed prices compared to wheat and wool. Australia has a land base to significantly increase canola area seeded.

Canola is a tiny seed, which means sowing depth must be controlled to minimise patchy germination. The current sowing practice is to lightly cover the seed with soil, which ensures more protection from drying out post-germination.

Canola is generally sown in autumn (late April/early May), develops over winter, flowers in the spring and is harvested early summer (Late November/early December) with a growing period of around 180-200 days

Climatic effects such as sudden heat waves can reduce yields and hot dry conditions can limit oil content, however summer weather ensures low moisture at harvest (<6% moisture). Carry-in stocks of canola are minimal because of a lack of on-farm storage.

Canola is a good rotational crop, acting as a break crop for cereal root diseases. However for disease-related reasons, a rotation period of 3-5 years is required for canola crops. Moreover, if on-going research on combating fungal root disease in wheat by seed inoculation proves successful, canola area will be pressured when canola prices fall.

4.6.2 Production

Current canola oil production is about 10% of Australian diesel oil consumption. Canola seed production in 2000/2001 was 1.6 Mt across a total cropping area of 1.3 Mha giving a gross yield of 1.26 t/ha of canola seeds. Oil yield from the seed is around 40% giving a total crude canola oil production of approximately 640,000 tonnes. If all of this were processed into biodiesel, with losses through refining of approximately 2.5% the potential Australian biodiesel production from canola would be 624 kt. This compares with a 1998 on-road diesel consumption in Australia of 6,600 kt (NGGIC, 2000).

Australian Oilseed Crush Capacity in 1997 was approximately 1.3 Mt p.a. made up of 0.40 Mt canola, 0.36 Mt cottonseed, 0.16 Mt sunflower seed, 0.15 Mt soybeans, 15,000 t other oilseeds

Crushing plant locations as in 1997 are detailed in Table 4.8. It is likely that more capacity has been introduced in Western Australia, where canola production has increased dramatically over the last five years. Refining capacity for vegetable oils in 1997 was approximately 500,000 tonnes with both crushing and refining capacity being utilised at around 90%. (Adaptation and Grain Policy Directorate, 2001).

Table 4.8
Crushing plant locations and capacity for vegetable oil extraction in Australia

Location – Company	Capacity (‘000 t)
Brisbane - Cargill	125
Moree(NSW) - Cargill	120
Narrabri(NSW) – Cargill	350
Maitland(NSW) – WC Caines	50
Newcastle - Cargill	230
Sydney - Seedex	25
Canowindra (NSW) - Aust. Country Canola	12
Cootamundra – Cootamundra Oilseeds	5
Grong Grong (NSW) - Ausguang	100
Footscray - Cargill	130
Numurkah(Vic) – Riverland	80
Millicent(SA) – Seedex	25
Pinjarra(WA) – Davison Industries	25

Source: (Adaptation and Grain Policy Directorate, 2001)

Australian production in 2000/2001 decreased by one third from 1999/2000 due to lower area seeded, and lower yields related to severe drought across Western Australia. Exports are expected to decrease by almost 40% to 1.2 Mt. The production outlook is forecast to remain stable at 1.6 Mt as expected decline in seeded area is offset by a return to normal yields. Aventis and Monsanto plan to introduce Liberty Link and Round Up Ready canola to Australia in 2002 with exports of GMO canola occurring by 2003. GMO varieties are expected to increase yields by 25%.

Figure 4.2 shows the distribution of oilseed production in Australia in average hectares planted per farm. It reveals intensive activity in the inland area of south Western Australia and also in the Mallee region of western New South Wales. This is supported by data on state by state canola production, which is shown in Figure 4.3. While Western Australia has the largest area under cultivation for canola, its lower production rates per hectare mean that it is only slightly higher than New South Wales in terms of canola production.

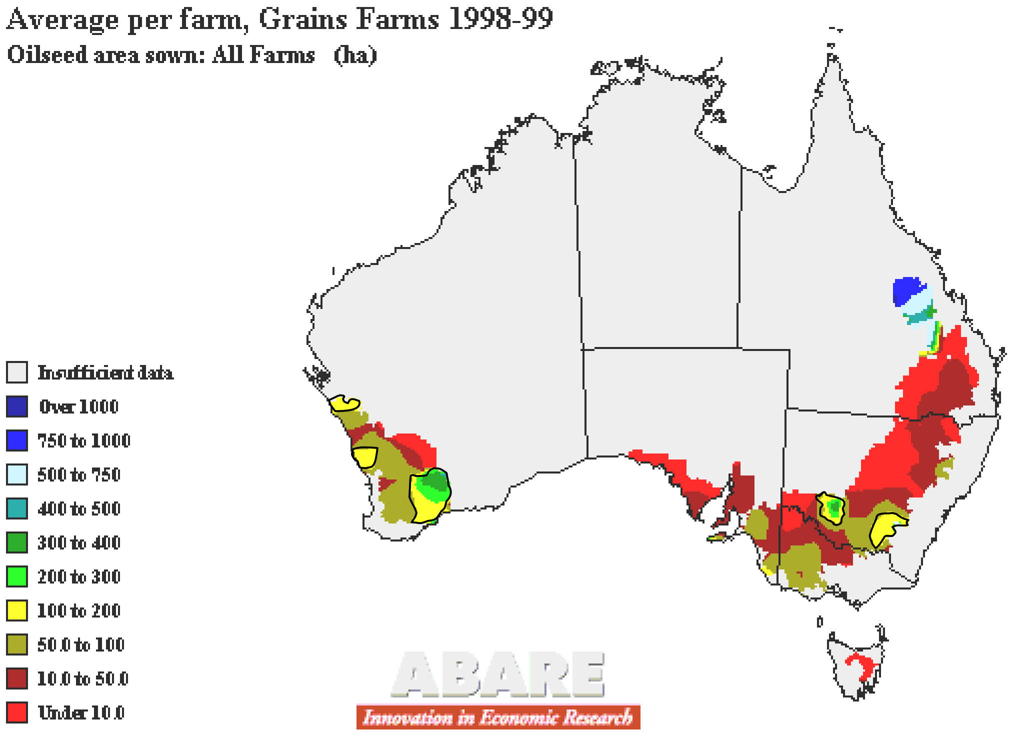
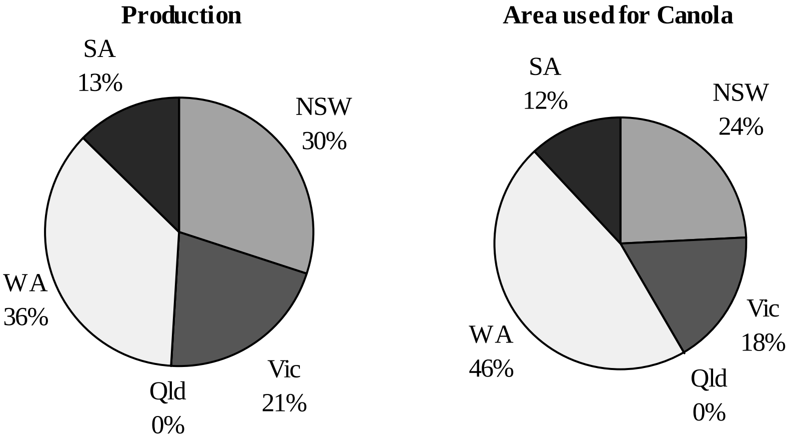


Figure 4.2
Location of Oil Seed production across Australia



Source: (Australian Bureau of Agricultural Research Economics, 2000)

Figure 4.3
Canola production and land area used for farming by state for 2000-2001 Australia

4.6.3 Fertiliser

Canola is a nutrient hungry crop compared to other winter crops, cereals, and grain legumes. The major nutrients required for Australian canola are nitrogen, sulfur, phosphorous, and zinc.

Available data regarding fertiliser input to canola farming has been collected from various sources, and is shown in Table 4.9. The second from the right column shows the nutrient removal per hectare of canola crop. Theoretically this is the amount needed to be replenished for canola agriculture to be sustainable. However, biomass from the canola plant is left behind in the field, which returns some of the nutrient to the soil. Recommendations for nutrient addition from the fertiliser producers is shown in the second column but varies widely according to soil conditions, and expected yield. The third column is recommendations from the Victorian Department of Natural Resources and Environment (NRE) in regards to the application rates of nitrogen for canola after cereal and pasture crops. The fourth column is estimated from figures on nitrogen and phosphorous usage data in oilseed growing areas from ABARE – Agaccess database (Australian Bureau of Agricultural Research Economics, 2000). (See Figure 4.4 and Figure 4.5, which overlay the oilseed growing area over the nitrogen and phosphorous usage maps.)

Table 4.9
Information sources regarding fertilizer use when farming canola in kg/ha

Canola	Hi-Fert Recommendation[1]	Nitrogen application kg/ha[3]	Grain Access Data average fertilizer application in oilseed growing areas[2]	Nutrient removal kg per ha[1]	Data estimate used in this study
Nitrogen	**0-100**	**A=100, B=60-80**	**20 to >30**	**82**	**20**
Phosphorous	**15-25**		**10 to 20**	**14**	**10**
Sulfur	**0-30**			**20**	**Supplied in other fertiliser**
Zinc	**0-3**			**0.080**	**0**

A=after cereal crop **B=after pasture crop**

[1](WMC Fertilizers Pty Ltd, 2000)
[2](Australian Bureau of Agricultural Research Economics, 2000)
[3](Natural Resources and Environment, Victoria, Canola, www.nre.vic.gov.au, 2000) Des Whitfield Agronomist, NRE.

The only other data is from cost estimates for growing canola provided by NRE for 1995/96 (see Table 4.11), which has the cost of fertilisers at $65 per hectare for the Mallee in Victoria. Assuming nitrogen costs around $1.50 per kilogram (currently around $2 per kilogram elemental N after five years of inflation and GST) and phosphorous at around $6 per kilogram (currently around $8-10 per kilogram of elemental P after five years of inflation and GST), 20 kg of N and 10 kg of P would cost around $90. This discrepancy may be put down to higher fertility in the Victorian Mallee compared with other canola growing regions, particularly in Western Australia (which is supported by the nitrogen and phosphorous data in Figure 4.4 and Figure 4.5). Due to a lack of supporting data, sulfur and zinc were assumed to be supplied in existing fertiliser production.

The addition of fertiliser and cropping can lead to soil acidification. Data from the Land and Water Research Development Corporation (Australian Bureau of Statistics 1996) has liming costs for canola in South Australia at around $9 per ha per year in 1996 (averaged over a 15 year period). Using a price of 10c per kilogram from lime in 1996, a lime usage of 90 kg/ha/year was arrived at for use in the study.

The process of cultivation and application of fertiliser also has an impact on emissions of nitrous oxide (N_2O). The National Greenhouse Gas Inventory has emission listed for crop production of 0.45 kg N_2O per hectare of crop per year. For fertiliser application it has an emission factor of 1.25% of Nitrogen applied ending up as N_2O emission. This results in a total N_2O emission per hectare of 0.85 kg as is shown in Table 4.10.

Table 4.10
Nitrous Oxide Emissions from Fertiliser and Soil Disturbance

Nitrogen Source	Fertiliser Applied per year kg	Emission Factor % of N applied[1]	kg N ha^{-1} $year^{-1}$	Conversion Factor (N - N_20) [1]	N_2O per Ha
Soil disturbance			**0.29[1]**	**1.57**	**0.46**
Fertiliser application	**20**	**1.25%**	**0.25**	**1.57**	**0.39**
Total					**0.85**

Source:(NGGIC, 2000) Agricultural Soils 4D-1

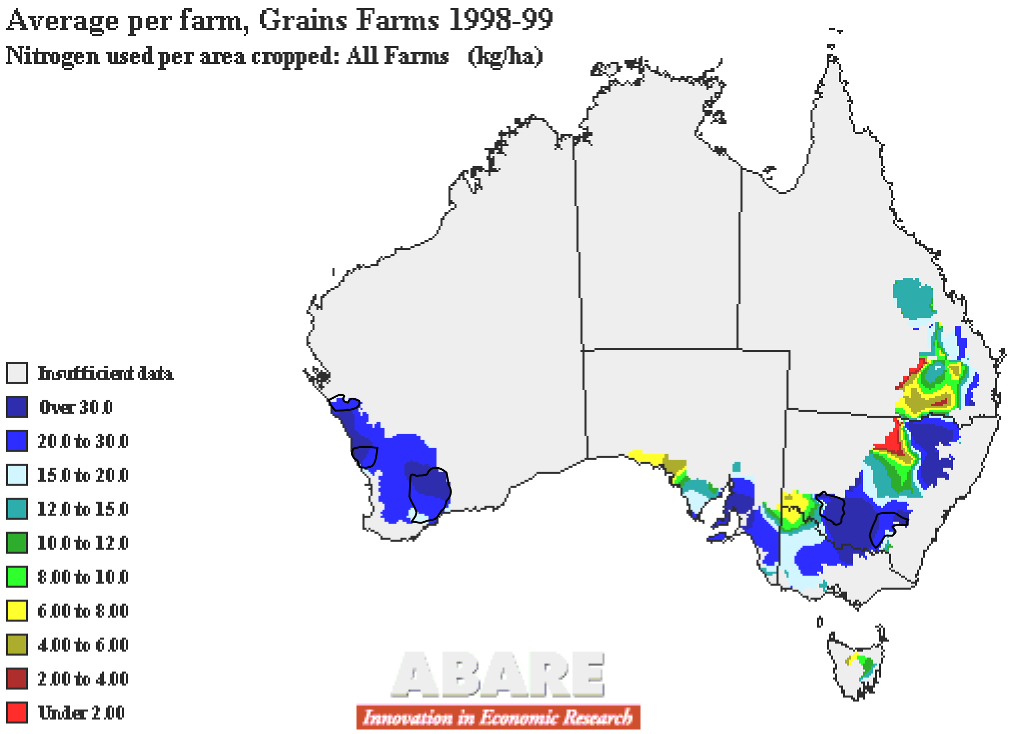


Figure 4.4
Elemental Nitrogen use per ha across Australian Farms with major oilseed production areas outlined.

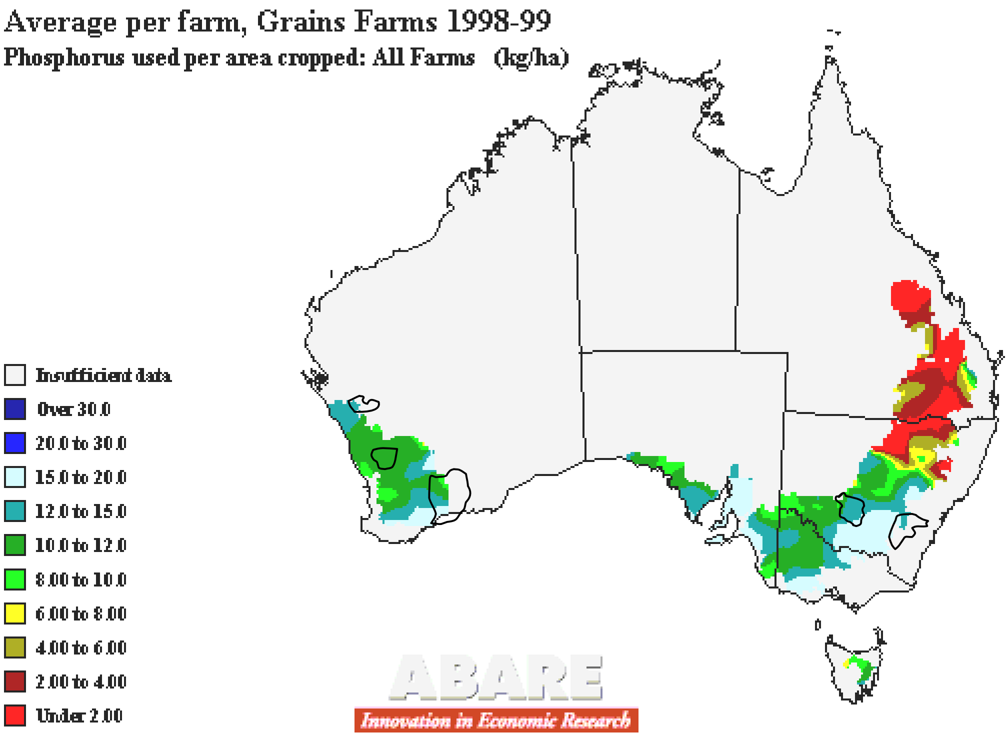


Figure 4.5
Elemental Phosphorous use per ha across Australian Farms with major oilseed production areas outlined.

Table 4.11
Variable costs for canola grower in the Wimmera, 1995/96

Item	$/ha
seed	13
fertiliser	65
herbicides and insecticides	36
tractor costs	20
harvesting	31
other	10
total variable costs	175

Source: [Natural Resources and Environment]

4.6.4 Water requirements.

The canola crop does not require excessive amounts of water. Although high temperatures and low water content limits oil yield, the cost of irrigating canola crops does not warrant such practices. Moreover industry experts believe that yield is affected more by disease, but at this stage are unsure about the exact nature of the disease and how it affects oil content. Data on irrigation practices within the field crop industry is lacking even for major crops such as wheat, consequently canola water use data does not exist presently (Gammie, 2001).

4.6.5 Fuel Use

Fuel use data on farms across Australia (Figure 4.6), shows that the oilseed growing areas in Western Australia have fuel use of around \$15-20 per ha while in New South Wales the fuel cost is around \$30 to more than \$45 per ha. Overseas data from rapeseed production (Table 4.12) indicates a total diesel usage of 70 litres per ha. At a rate of 45c/litre for diesel (in 1998/99 with 80c pump price and 35c rebate for primary producers) the Australian data suggests a range from 33-44 litres per ha for Western Australia, and 66 to 100 litres per ha in New South Wales. With one third of the production being based in Western Australia at an average of 38 litres and two third in New South Wales, Victoria and South Australia at an average of 83 litres, a final estimate of 68 litres per hectare was used.

Table 4.12
Fuel use data from rapeseed production in European RME LCA

Fuel	**L/ha**
Ploughing	20.3
Harrowing	8.3
Seed bed preparation	12
Sowing	4.9
Fertilizer application	7.6
Harvesting	17
Total	70.1

Source: (Ceuterick and Spirinckx, 1997)

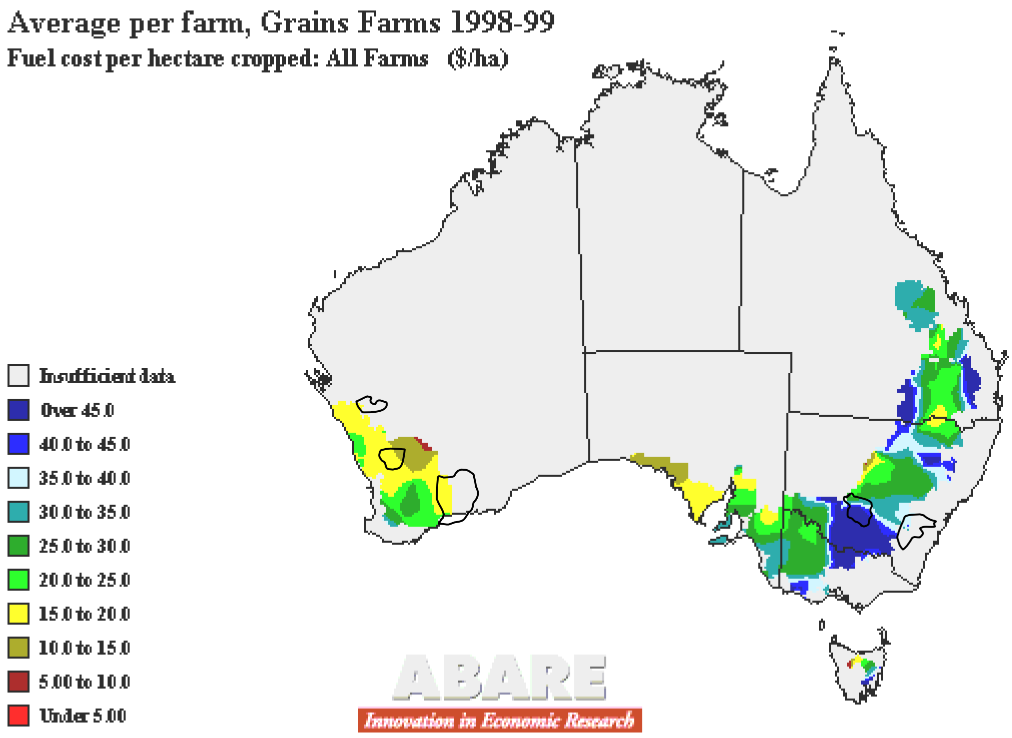


Figure 4.6
Fuel cost per ha across Australian Farms with major oilseed production areas outlined.

4.6.6 Chemical crop protection

Early weed control needs to be effective to ensure the canola crop establishes. Both broadleaves and grasses need to be controlled to ensure healthy crop development. One of the most common herbicides used in the agricultural industry is *Roundup*. As a dry formula the application rate is 265 g-660 g/ha and costs $120 per 11 kg container. In its liquid state the application rate is 400 ml-1.2 L/ha and costs $90 per 20 L container. (Prices based on bulk purchasing prices-E.E. Muir & Sons.)

Disease control is required to prevent fungal, bacterial, and viral pathogens. The impact of disease on canola crops is dependent upon region, climate, land management, as well as the previous crop harvested. Consequently application rates vary depending on the factors listed above.

High levels of insecticide are often unavoidable for insect pest control to ensure high yields of good quality canola seed. Pesticide application rates are influenced, like fungicides, by the factors listed above.

Figure 4.7 shows a map of spray usage per ha for Australian farms with the canola growing areas overlaid. It indicates that spraying costs in 1998-99 were around $40-$45 per ha in the oilseed growing areas.

The energy involved in the fertiliser and pesticide production and application, and the upstream emissions as a result of the production and application have been included in the calculation of upstream emissions.

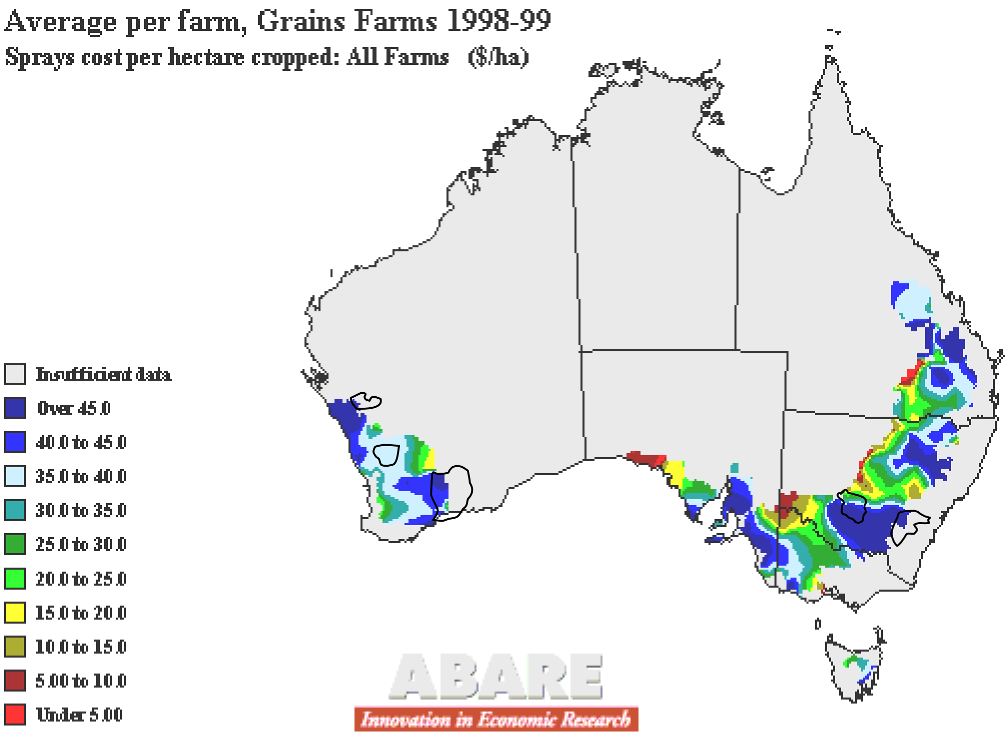


Figure 4.7
Spray cost per ha farm across Australian Farms with major oilseed production areas outlined.

Table 4.13
Suggested crop protection application rates for canola (Coombs, 1994)

Herbicide kg/ha	Pesticide kg/ha	Fungicide kg/ha
1.9	0.7	1.4

4.6.7 Co-products for canola seed production

Canola seed is produced as part of the canola crop and represents a small part of the total crop biomass. While the seed is clearly the primary product from canola, the other parts of the plant, the straw and stump and root material, also provide some economic benefits. The straw may be used for feed, or used as an energy source in the production of biodiesel. The straw and the root material may also be returned to the soil to replace nutrient material.

In the Flemish LCA of biodiesel (Ceuterick and Spirinckx, 1999) from rapeseed, the rape straw was assumed to be used for some economic purpose and was treated as product of equal value, per unit of dry mass. In a UK study (EcoTec Research and Consulting Ltd, 1999) straw was included as a fuel for biodiesel production, therefore eliminating the need to estimate the relative value of straw and the seed. In Australia the current practice is to leave the straw and stubble in the field as its quality does not warrant production into straw for feed, and the quantity is not sufficient for field burning (Gammie, 2001).

4.6.8 Drying, storage and handling

European data on rapeseed processing states that the seed requires drying treatment to reduce the moisture content from 15% to below 9% for storage purposes (Ceuterick and Spirinckx, 1999). In Australia, the canola seed contains approximately 6-10% moisture so no drying stage is required (Norton, 2000) and no drying was incorporated into the upstream activities. Transport of canola from the farm to oil processing is assumed to be relatively short given the locations of oil processing facilities detailed in Table 4.8. A value of 150 km by road is assumed in this study.

4.6.9 Oil extraction and refining

Data on canola oil extraction and refining is not available. However the canola refining process described by the Canadian Canola Council (Canola Council of Canada, 2001) is very similar to that used for rapeseed as described in the Flemish rapeseed biodiesel LCA (Ceuterick and Spirinckx, 1997), for which process data is available. The data and processes are described below.

Cleaning of the incoming seed is undertaken to remove plant material and other debris. The seeds are then dehulled, comminuted and heat-treated. The seeds are then pressed to produce oil (first press oil) and seed cake with an oil content of around 14 to 18%. This occurs at a temperature of between 72-84°C. The seed cake is then treated to a solvent extraction process (hexane), to decrease the oil content of the cake to between 3 and 5%. The hexane solvent is recycled through the process with a net loss of 1.5 kg per tonne of seeds handled. This is assumed to be lost as an emission to air. The seed cake is then toasted to remove the solvent before being sold as a protein source for feedstock. The oil hexane water mixture is then heated to remove water and recover the hexane, leaving the crude oil. Process data for these steps are shown in Table 4.14.

Table 4.14
Process input and outputs for oil extraction of canola

Inputs	Unit	Value
Oils seeds	kg	1000
Electricity[1]	kWh	45
Steam (natural gas fired)[2]	kg	310
Hexane[1]	kg	1.5
Outputs		
Crude Oil[3]	kg	399
Seed Cake[3]	kg	598
Solid Waste[1]	kg	3
Hexane to Air[1]	kg	1.5

Notes

[1] Taken from rapeseed data (Ceuterick and Spirinckx, 1999)

[2] Taken from rapeseed data (Ceuterick and Spirinckx, 1999) based on energy input of 3.64 MJ/kg steam

[3] Based on expected canola oil yield of 40% less solid waste produced

The input and outputs of this process need to be allocated between the two valuable outputs – canola oil and meal. Canola oil is traded on the Western Canadian Exchange, which determines the price of canola. As with all commodities, the price fluctuates daily. The price is reported in the Australian Financial Review and on 29 March 2001 was C$281 per tonne. Canola meal is valued at US$162 per tonne (Canola Council of Canada, 2001). Due to the different value of the production a mass-based allocation would not be appropriate, so an economic allocation has been used and is shown in Table 4.15 with 63% of the burdens of the canola production and extraction process being allocated to the canola oil.

Table 4.15
Allocation of environmental burdens between canola oil and meal

Product	Yield kg	Value per tonne $US	Value of Yield	Allocation %
Crude Oil	399	411	164	63%
Seed Cake	598	162	97	37%

Crude canola oil refining

The crude canola oil from the extraction process contains phosphatides, gums and other colloidal compounds, which can cause problems through settling during storages. Therefore a refining process using steam removes them. During this process 2.5% of the oil is lost as a solid waste. Process data (shown in 4.16) is taken from the Flemish LCA for rapeseed oil, although their reported loss is 4%.

Table 4.16
Process input and outputs for oil extraction of canola

Inputs	**Unit**	**Value**
Crude Oil	kg	1000
Electricity[1]	kWh	10
Steam (natural gas fired)[2]	kg	80
Outputs		
Refined Oil[3]	kg	975
Solid Waste[1]	kg	25

Notes

[1] Taken from rapeseed data (Ceuterick and Spirinckx, 1999)

[2] Taken from rapeseed data (Ceuterick and Spirinckx, 1999) based on 2.5% of energy input as steam with an energy density of 3.64 MJ/kg

4.7. Soybean

Soybeans are a bushy, leguminous plant, *Glycine max*, native of South-East Asia that is grown for the beans, which are used widely in the food industry, for protein in cattle feed and for oil production.

Soybeans are grown predominantly in the wheat belts of Queensland and New South Wales and to a lesser extent in Victoria, as is shown in Figure 4.8. A total of 53 000 ha produced 105,000 tonne of soybeans in 2000 (Australian Bureau of Agricultural Research Economics, 2001), giving a yield of 2t/ha of soybeans.

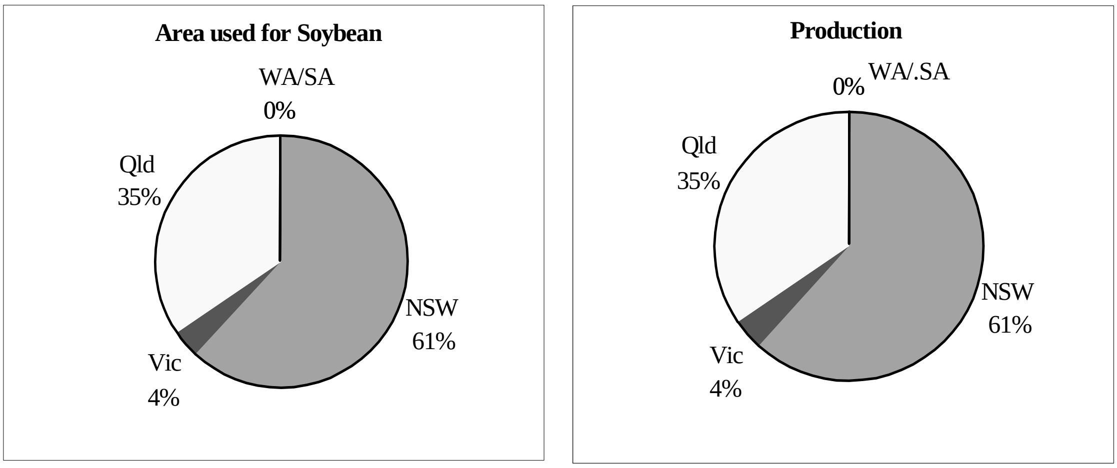


Figure 4.8
Soybean area and production by state 2000 Australia

Available overseas information regarding fertiliser input to soybean farming is shown in Table 4.17. This is contrasted with data on nitrogen and phosphorous usage in the wheat growing areas from ABARE – Agaccess database (Australian Bureau of Agricultural Research Economics, 2000). The final values chosen in the study are also given. These were the values applicable to soybeans, except for phosphorous where it was felt that the Australian data indicated that the overseas growers were over-applying phosphorous.

Table 4.17
Information sources regarding fertiliser use when farming soybeans and wheat

Soybean	**NREL Data**[1]	**Grain Access Data average fertiliser application in pulse growing areas**[2]	**Data used in Study**
	kg/ha	kg/ha	kg/ha
Nitrogen	15	20 to >30	15
phosphorous	25	6 to 12	12
potash	20		20

[1](Sheehan et al., 1998)
[2](Australian Bureau of Agricultural Research Economics, 2000)

Fuel use data on farms across Australia from ABARE, show that in the wheat belt of Queensland fuel costs are around $15 to $25 per hectare. In New South Wales costs vary from $25 to $35, or more. This equates to fuel usage of between 33L and 77L using a fuel price of 45c/L for diesel (in 1998/99 with 80c pump price and 35c rebate for primary producers). The NREL study in the United States has fuel usage for soybean growing at 84L comprising of different fuels as shown in Table 4.18. It appears from the range of fuels in Table 4.18 that some other vehicle transport is included in the data (gasoline and LPG) which we may account for separately in product transport to oil processing. Ignoring the non-diesel fuels, the NREL data of 57.5 L is almost the same as the midpoint of the range given by the ABARE data of 55 L. Therefore the 55 L figure has been used in the study for soybean production in Australia.

Table 4.18
Soybean Agriculture System Inputs from NREL study for USA

Energy:	**Gal./acre**[1]	**L/ha**	**Density**	**kg per ha**
Gasoline	3.11	29.1	0.74	39.6
Diesel	5.29	49.5	0.86	57.4
LP	0.38	3.6	0.51	7.0

[1] Source:(Sheehan et al., 1998: Table 49)

4.7.1 Crop protection

The NREL study has a value of 4 lb per acre or 4.5 kg/ha for chemical application, which is listed predominantly as herbicides. The chemical directory in the Australian grains reference book (Coombs, 1994) suggests herbicide applications of around 1-2 litres per ha, and insecticides at around 0.5 to 2.5 L/ha. Assuming density close to this gives 1.5 to 4.5 kg of pesticide per ha of soybean crops. A figure of 3 kg/ha has been chosen for use in the study.

The only data available on pesticide manufacture is from a Danish study (Weidema, 1995) in which 60 MJ of ethane is used as feedstock and 164 MJ of process heat is required for manufacture. This data has been used for generic pesticide inputs in the absence of other information.

4.7.2 Drying, storage and handling (through to oil extraction and refining)

Due to the low volume of soybeans processed in Australia, very little data is available locally on oil extraction and processing. Data from the United States on soybean handling and processing (Sheehan et al., 1998) has been used for this study. Details of the process are provided by Sheehan et al. (1998), and it is similar to other seed crops. For transport of soybean to oil processes a value of 150 km by road is assumed in this study, which is the same default value used for canola

The soybean are dried, dehulled, preconditioned with heat, crushed to extract the initial first press oil, before the remaining oil is extracted using a solvent (hexane) which is largely recovered in the process. The oil is then degummed before being ready for conversion to biodiesel. Energy and material inputs and outputs from the NREL study are given in Table 4.19 and Table 4.20.

Table 4.19
Process inputs for 1 tonne for soybeans

Inputs	Value	Unit
Receiving and Storage		
Australian Electricity	21.3	kWh
Soybean Drying		
Natural Gas Energy	1.1	GJ
Dehulling		
Natural Gas Energy	0.173	GJ
Australian Electricity	21.59	kWh
Oil extraction		
Natural Gas Energy	0.087	GJ
Australian Electricity	0.38	kWh
Solvent Recovery, degumming oil and water treatment		
Natural Gas Energy	0.173	GJ
Australian Electricity	2.78	kWh
Meal processing		
Hexane input	2.02	kg
Natural Gas Energy	0.557	GJ
Australian Electricity	19.9	kWh

Source: (based on Sheehan et al., 1998)

Table 4.20
Process Outputs for 1 tonne for soybeans

Crude soybean oil	170	kg
Soymeal	760	kg
Hexane to Air	1.72	kg
Solid Waste [1]	70	kg

Source: (Sheehan et al., 1998)

[1] This is based on a mass balance of input of soybeans – some of this material may be lost in waste water.

4.7.3 *Allocation procedure for meal and oil from soybeans*

The input and outputs of this process need to be allocated between the two valuable outputs – soybean oil and meal. Soybean oil is currently valued at around US$491 per tonne while the meal is valued at US$205 per tonne[1]. Due to the different value of the production a mass based allocation would not be appropriate, so an economic allocation has been used and is shown in Table 4.15 with 33.9% of the burdens of the soybean production and extraction process being allocated to the oil.

Table 4.21
Allocation of environmental burdens between soybean oil and meal

Product	Yield kg	Value per tonne $US	Value of Yield	Allocation %
Crude Oil	170	491	83	33.9%
Soybean Cake	760	214	163	66.1%

4.8. *Tallow*

4.8.1 *Background*

Meat rendering is the processing of carcass waste from the meat industry. The process involves crushing the raw material, followed by the indirect application of heat. This evaporates the moisture and enables the fat, known as ‘tallow’, to be separated from the high-protein solids, known as ‘greaves’. Pure tallow is a creamy-white substance. The greaves are pressed, centrifuged or subjected to a process of solvent extraction to remove more tallow, before being ground into meat and bone meal (MBM) (Matravers et al., 2000).

According to the UK report (Matravers et al., 2000), most rendering plants were ‘dry rendering’ (atmospheric) batch processors up until the 1960’s. From the 1970s onwards, a variety of continuous rendering systems became available. They all use heating, separation and cooling on a continuous flow basis - essentially, raw material was fed in one end of the cooker and the finished product ejected out the other (Matravers et al., 2000). Solvent extraction appears to have fallen out of favour in most countries due to the cost and hazards.

4.8.2 *Allocation issues for biodiesel from tallow*

The main bioproducts from the meat industry are hides, offal, meat and bone meal and tallow. “The beef industry alone contributes $400 million worth of co-products annually, which are estimated to supply around one-fifth of the total value of an animal.”(Meat and Livestock Australia, 2001).

There are two possible approaches to determining the impacts from increasing the use of tallow for biodiesel. One is to assume that increased demand for tallow will marginally increase the demand and consequent production of beef products in general. This is not very likely as beef demand is the main determining factor in beef cattle production (assuming this increase is linked to the economic value of the by products, then this is referred to as an economic allocation of co-products). The second approach is to assume that tallow will be taken from other current users of tallow to meet the demand for tallow in bio-diesel. These other uses include soap and cosmetic applications and use in animal feedstocks. Many vegetable oils can be used in place of tallow for the soap and for cosmetic purposes, and are

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[1] The Australian Financial Review of 1 June 2001 quotes soybean futures as US$4.36 per bushel, soymeal as US$160 per ton, and soyoil as US$14.80 per lb.

assumed to be the most likely replacement for displaced tallow. While canola is not a good oil for soap production, it is cheap to produce and could therefore be expected to increase in production to meet increased demands for oils (needed for soap and other uses) created by the diversion of tallow into bio-diesel.[2] The impact of diverting tallow to bio-diesel is therefore modelled as the production of canola to replaced tallow displaced into biodiesel as shown in Figure 4.9. The LCA Standards (International Standards Organisation, 1997) refer to this type of modelling as system boundary expansion, which avoids allocation between the different beef by-products.

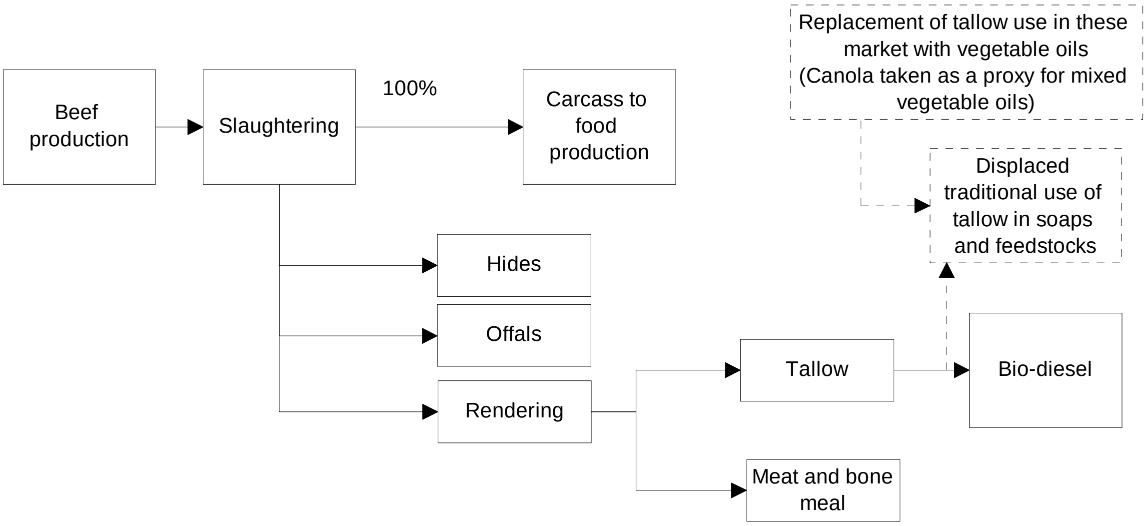

Figure 4.9
Allocation of beef impact with system boundary expansion to include implications of using tallow in biodiesel production

The alternative approach, mentioned above, is the economic allocation of emissions between the different by-products. Table 4.22 outlines estimates of the prices per head of beef for different products and co-products with the yield of production and the allocation percentage used in the study. Rendering products represent approximately 3.6% of the value of beef cattle.

Table 4.23 details the value and allocation percentage for rendering products showing that tallow represents 45% of the economic value of rendering products, which equates to 1.6% of total beef value. This leads to an allocation of beef production impacts to tallow as shown in Figure 4.10.

The modelling of beef production has been simplified in the study. From a greenhouse perspective the beef industry is responsible for a significant proportion of the greenhouse emissions due to methane from enteric fermentation in the intestines of cattle, and N_2O from faecal matter and urine. Due to its importance, these emissions are included in the beef (and therefore in part in the tallow) production inventory.

While numerous animal products other than beef contribute to total tallow production, for reasons of simplicity this study will assume all tallow is derived primarily from beef products (the beef industry is estimated to provide 60% of the input to meat rendering).

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[2] Note that due to BSE and other cattle borne diseases the dynamics of tallow use are likely to change over the next few years, however no clear indication has been found as to how this might affect the use of allocation procedure for tallow in bio-diesel.

Table 4.22
Allocation of beef products and co-products

	Average yield per kg of beef cattle	Average value of product per head of cattle (A$)	Allocation %
Beef Product	0.55[3]	800[1]	80.2%
Hides	0.060	90[2]	9.1%
Render Products	0.292[2]	36[2]	3.6%
Offals	0.098[2]	71[2]	7.1%

[1] At estimated US$400 per head
[2] Averaged across for Australian beef types (Prime Steer, US Cows, Japan Grass Fed Steer, Japan Grain Fed Steer) from (Meat and Livestock Australia, 2000)
[3] Estimated meat yield of 55%

Table 4.23
Allocation of rendering products based on economic value

	Average yield kg per kg render feedstock	Average price per head of cattle (A$)	Allocation %
Tallow	0.54	16.23[1]	0.45
Meat and Bone Meal	0.46	19.76[1]	0.55

[2] Averaged across for Australian beef types (Prime Steer, US Cows, Japan Grass Fed Steer, Japan Grain Fed Steer)
Source: Adapted from (Meat and Livestock Australia, 2000)

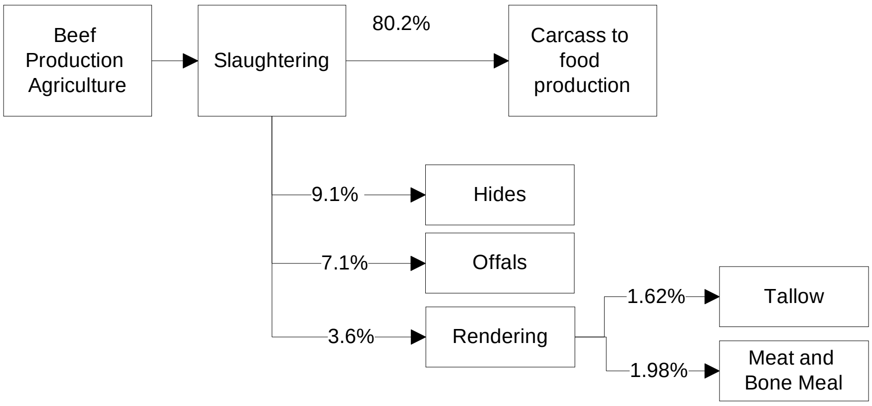

Figure 4.10
Summary of tallow production allocation from beef cattle agriculture

4.9. *Recycled Waste Cooking Oil*

4.9.1 Background

Cooking oils, used for frying food have a limited life in food production due to contamination of the oil by food material. The disposal of waste cooking oil into landfill is generally prohibited in Australia[3], so that at the present time cooking oil needs to be collected from the

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[3] For Victoria - Environment Protection (Prescribed Waste) Regulations 1998 S.R. No. 95/1998, Part B Prescribed Industrial Wastes Waste cooking oils unfit for their original intended use.

food industry for recycling or treatment for use in stockfeed. Current possibilities for the processing of waste cooking oils appear to be:

- Treatment and use in stockfeed in Australia (EcoRecycle Victoria, undated)
- Export to Asia for soap or stockfeed production (Anthony & Cornish, 2001)
- Use for production of biodiesel (Anthony & Cornish, 2001)

It is also clear that some waste cooking oil is not collected and is disposed of in landfill or other locations (Anthony and Corish, 2001). Biodiesel made from waste cooking oil has come to be known as McDiesel, because the largest source of waste cooking oil is McDonald's restaurants.

A sensitivity analysis has been included in the study to show the impact of assuming that the waste oil is of significant resale value, as has been suggested by some stakeholders. Under this alternate scenario 10% of the original value of the oil is assumed to be retained, and therefore 10% of the oil production impacts (assumed to be canola) are attributed to the waste oil.

4.9.2 Alternative technology association biodiesel project

The Alternative Technology Association (ATA) has undertaken some research into waste cooking oil generation and disposal by restaurants in the City of Moreland. They found the average restaurant (of those which responded), produced around 3000 litres of oil a year. Five per cent of the oil volume was reported as going to landfill (it is expected that this would be higher for the non respondents (Anthony, 2001).

In 1999, ATA received a small grant from the City of Moreland to establish a mini processing plant that could be used as a model for other small processing plants. Biodiesel production began in June 2000 and has been sold to various individuals and organisations, at a price between $1.50 and $2.00 per litre(Anthony and Cornish, 2001).

4.9.3 Allocation Issues for biodiesel from waste cooking oil

Current information on waste cooking oil collection indicates that large providers of oil are paid for their oil while small producers may have to pay to have their oil collected (Anthony, 2001). This suggests that in some situations the waste cooking oils collection is being driven by waste management imperatives and not by the recognised value in the oil. Following allocation guidelines developed by Weidema (1999), waste cooking oil can be seen as a "near to waste" co-product of the food production industry, that is not fully utilised (i.e. not all oil is currently recycled and there is little competition for waste cooking oil). Under this assumption only the impacts of recycling processes are allocated to the biodiesel with credits for avoided waste treatment processes being given to the biodiesel product. The difficult task for waste vegetable oil is determining the current waste treatment processes. Given poor quality of the information relating to waste cooking oil destinations, and the complexity of modelling upstream process for soap production in Asia, and the landfill impact of waste cooking oil being disposed of illegally, these systems have not been included at this stage. In effect waste cooking oil is modelled as a raw material with no upstream burdens that is input to the esterification process.

Given that collection of the oil is required for both the current waste treatment method, and for biodiesel production, there is no need to include collection as it can be assumed to be the same in each case.

4.10. European Work

The European life-cycle studies of the IEA Automotive Fuels Information Services were summarised by Beer et al. (2000). Since that time the British Association for Bio Fuels and

Oils (BABFO) produced a report (EcoTec Research and Consulting Ltd., 1999) that summarised the life cycle emissions of gaseous pollutants from diesel and biodiesel for the UK. Their results are summarised in Table 4.24.

Table 4.24
UK life cycle emissions for diesel and biodiesel used in a 2.5L Ford Transit van

		GHG (g/km)	SOx (mg/km)	NOx (mg/km)	PM (mg/km)	VOC (mg/km)	CO (mg/km)
Diesel	Upstream	33	207	145	4	416	19
Diesel	Tailpipe	245	80	1050	200	135	900
Diesel	Total	278	287	1195	204	551	919
Biodiesel (from straw)	Upstream	59	62	561	128	182	394
Biodiesel (from straw)	Tailpipe	0	20	1100	220	60	950
Biodiesel (from straw)	Total	59	82	1661	348	242	1344
Biodiesel (from gas)	Upstream	75	36	485	99	249	232
Biodiesel (from gas)	Tailpipe	0	20	1100	220	60	950
Biodiesel (from gas)	Total	75	56	1585	319	309	1182

Given the difference in vehicle types it is not possible to directly compare the results in Table 4.24 with those in Beer et al. (2000). Nevertheless the relative differences between diesel and biodiesel confirm some of the earlier findings – in particular the larger full fuel-cycle emissions of particulate matter from biodiesel when compared to diesel.

4.11. By-Products

During the production of biodiesel, by-products are formed. Straw, for instance, is a by-product of the production of rapeseed and the esterification of rapeseed oil produces glycerine. These by-products have a certain energetic value, the magnitude of which depends very much on the method used to determine energy-content. One way to express energy content is the calorific value of the by-product; another way is in terms of substitute energy - that is the energy saved when a certain fuel is replaced by use of the by-product. Thus the energy stored in the by-products cannot be compared directly with the energy value of biodiesel. The energy contents of, for instance, straw cannot serve directly as a diesel combustion fuel. For this reason, when calculating upstream emissions, the energy stored in by-products is considered of lower quality than the energy stored in biodiesel or diesel oil.

4.12. Full Fuel-Cycle Analysis of Emissions

The analysis given in this section deals with biodiesel as a fuel in its own right. In most cases biodiesel is used as a blend, or an additive, comprising about 20% of the diesel fuel (BD20). The exbodied emissions from such a blend can be calculated for the upstream emissions by using 80% of the diesel fuel exbodied emissions, and 20% of the corresponding biodiesel emissions given below. Tailpipe emissions do not appear to follow such a linear procedure. Tailpipe emissions for BD20 for buses and BD35 for trucks may be found in Beer et al. (2000).

In the tables below we consider two possible allocations for both tallow and waste cooking oil. The standard assumption is that both are waste products, and an expanded systems boundary approach was used to quantify their emissions. In both cases, an alternative allocation considers them to be marketable products.

4.12.1 Emissions on a mass per unit energy basis

The results obtained by using the SimaPro life-cycle model, along with the upstream and tailpipe emissions data specified in this chapter of this report, are given in Table 4.25 for the full life cycle for greenhouse gases and criteria pollutants. The upstream emissions and the tailpipe emissions that comprise these totals are given in Table 4.26 and Table 4.27 respectively. The greenhouse gas emissions and the economic weighted air pollutant emissions are graphed in Figure 4.11.

Table 4.25
Urban and total life cycle emissions (per MJ) calculated for diesel and biodiesel

Full Lifecycle	Units	LS Diesel	Canola biodiesel	Soybean biodiesel	Rape biodiesel	Tallow biodiesel	Tallow alternative allocation	Waste cooking oil biodiesel	Waste cooking oil alternative allocation
Greenhouse	kg CO_2	0.0858	0.0433	0.0326	0.0443	0.0420	0.0498	0.0062	0.0065
NMHC total	g HC	0.140	0.145	0.172	0.146	0.142	0.060	0.053	0.054
NMHC urban	g HC	0.111	0.134	0.163	0.134	0.131	0.059	0.052	0.053
NOx total	g NOx	1.044	1.296	1.283	1.314	1.292	1.184	1.179	1.184
NOx urban	g NOx	0.987	1.219	1.235	1.221	1.217	1.184	1.179	1.183
CO total	g CO	0.253	0.171	0.219	0.172	0.170	0.141	0.140	0.145
CO urban	g CO	0.242	0.155	0.210	0.156	0.155	0.141	0.140	0.144
PM10 total	mg PM10	40.7	29.9	29.4	30.5	29.8	27.6	27.5	27.5
PM10 urban	mg PM10	39.3	28.4	28.5	28.4	28.4	27.6	27.5	27.5
Energy Embodied	MJ LHV	1.18	0.42	0.45	0.43	0.41	0.17	0.14	0.15

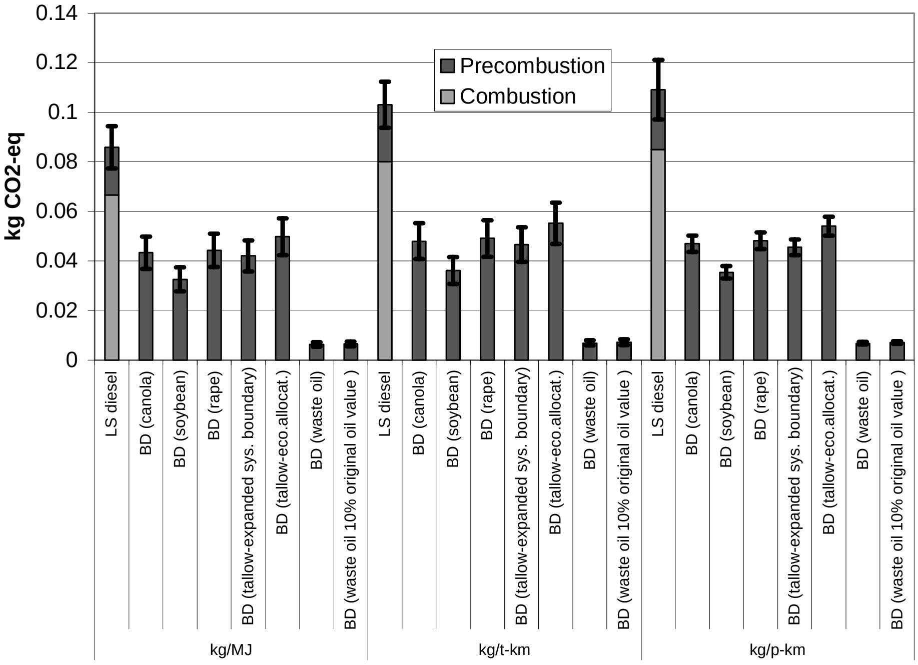

Figure 4.11
Life cycle emissions of fossil fuel greenhouse gases from biodiesel compared to low sulfur diesel

The results separate urban and rural emissions. Rural emissions may be evaluated as the difference between the total and the urban emissions. Emissions were assumed to occur in urban areas unless they were produced by a known rural or maritime activity.

Many of the values reported in the literature are in terms of g/MJ measured as useable energy from the engine driveshaft (normally represented as g/kWh), whereas the life-cycle calculations are consistent in setting all the calculations in terms of g/MJ based on the inherent chemical energy of the fuel. On average, this reduces quoted engine dynamometer values by a factor of three.

Table 4.26
Urban and total upstream emissions per MJ for diesel and biodiesel

Precombustion	Units	LS Diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Tallow biodiesel	Tallow alternative allocation	Waste cooking oil biodiesel	Waste cooking oil alternative allocation
Greenhouse	kg CO_2	0.0191	0.0433	0.0326	0.0443	0.0420	0.0498	0.0062	0.0065
NMHC total	g HC	0.0565	0.141	0.168	0.142	0.138	0.0564	0.0494	0.0503
NMHC urban	g HC	0.027	0.130	0.159	0.130	0.127	0.055	0.049	0.049
NOx total	g NOx	0.100	0.140	0.127	0.158	0.136	0.028	0.023	0.027
NOx urban	g NOx	0.043	0.062	0.079	0.064	0.061	0.027	0.022	0.027
CO total	g CO	0.023	0.035	0.083	0.035	0.033	0.005	0.004	0.008
CO urban	g CO	0.012	0.019	0.074	0.019	0.019	0.005	0.004	0.008
PM10 total	mg PM10	5.42	2.51	2	3.13	2.43	0.219	0.166	0.166
PM10 urban	mg PM10	4	1.01	1.07	1.05	0.982	0.206	0.156	0.156
Energy Embodied	MJ LHV	1.18	0.42	0.45	0.43	0.41	0.17	0.14	0.15

Table 4.27
Urban and total tailpipe emissions per MJ from diesel and biodiesel

Combustion	Units	LS Diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow)	Biodiesel (waste cooking oil)
Greenhouse	kg CO_2	0.0667	-	-	-	-	-
NMHC total	g HC	0.0835	0.0039	0.004	0.004	0.0038	0.0038
NMHC urban	g HC	0.0835	0.0039	0.0040	0.0040	0.0038	0.0038
NOx total	g NOx	0.944	1.156	1.156	1.156	1.156	1.156
NOx urban	g NOx	0.944	1.156	1.156	1.156	1.156	1.156
CO total	g CO	0.230	0.136	0.136	0.136	0.136	0.136
CO urban	g CO	0.230	0.136	0.136	0.136	0.136	0.136
PM10 total	mg PM10	35.3	27.4	27.4	27.4	27.4	27.4
PM10 urban	mg PM10	35.3	27.4	27.4	27.4	27.4	27.4
Energy Embodied	MJ LHV	0	0	0.000	0.000	0.000	0.000

4.12.2 Vehicle emissions - trucks (g/km)

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 4.28
Urban and total life cycle emissions per km for trucks calculated for diesel and biodiesel

Full LC		**LS Diesel engine**	**Canola biodiesel**	**Soybean biodiesel**	**Rape biodiesel**	**Tallow biodiesel**	**Tallow alternative allocation**	**Waste cooking oil biodiesel**	**Waste cooking oil alternative allocation**
Greenhouse	kg CO_2	0.9250	0.4310	0.3250	0.4410	0.4180	0.4960	0.0705	0.0736
NMHC total	g HC	1.509	1.439	1.709	1.449	1.409	0.600	0.597	0.607
NMHC urban	g HC	1.192	1.329	1.619	1.329	1.299	0.588	0.587	0.597
NOx total	g NOx	11.250	12.895	12.775	13.075	12.855	11.784	11.764	11.814
NOx urban	g NOx	10.638	12.125	12.292	12.144	12.112	11.775	11.757	11.807
CO total	g CO	2.723	1.699	2.184	1.707	1.689	1.407	1.403	1.450
CO urban	g CO	2.612	1.545	2.088	1.548	1.540	1.404	1.400	1.447
PM10 total	mg PM10	438.4	297.5	292.4	303.6	296.7	274.6	274.3	274.3
PM10 urban	mg PM10	423.1	282.6	283.1	282.9	282.2	274.5	274.2	274.2
Energy Embodied	MJ LHV	12.7	4.14	4.5	4.25	4.05	1.69	1.61	1.65

Table 4.29
Urban and total precombustion emissions per km for trucks calculated for diesel and biodiesel

Precombustion		LS Diesel (Aus)	Canola biodiesel	Soybean biodiesel	Rape biodiesel	Tallow biodiesel	Tallow alternative allocation	Waste cooking oil biodiesel	Waste cooking oil alternative allocation
Greenhouse	kg CO_2	0.2060	0.4310	0.3250	0.4410	0.4180	0.4960	0.0705	0.0736
NMHC total	g HC	0.609	1.4	1.67	1.41	1.37	0.561	0.558	0.568
NMHC urban	g HC	0.292	1.290	1.580	1.290	1.260	0.549	0.548	0.558
NOx total	g NOx	1.080	1.390	1.270	1.570	1.350	0.279	0.259	0.309
NOx urban	g NOx	0.468	0.620	0.787	0.639	0.607	0.270	0.252	0.302
CO total	g CO	0.243	0.343	0.828	0.351	0.333	0.051	0.047	0.094
CO urban	g CO	0.132	0.189	0.732	0.192	0.184	0.048	0.044	0.092
PM10 total	mg PM10	58.4	25	19.9	31.1	24.2	2.17	1.87	1.87
PM10 urban	mg PM10	43.1	10.1	10.6	10.4	9.77	2.05	1.76	1.76
Energy Embodied	MJ LHV	12.7	4.14	4.5	4.25	4.05	1.69	1.61	1.65

Table 4.30
Urban and total tailpipe emissions per km for trucks calculated for diesel and biodiesel

Combustion		LS Diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow)	Biodiesel (waste cooking oil)
Greenhouse	kg CO_2	0.719	0.000	0.000	0.000	0.000	0.000
NMHC total	g HC	0.900	0.039	0.040	0.040	0.038	0.038
NMHC urban	g HC	0.900	0.039	0.040	0.040	0.038	0.038
NOx total	g NOx	10.18	11.51	11.51	11.51	11.51	11.51
NOx urban	g NOx	10.18	11.51	11.51	11.51	11.51	11.51
CO total	g CO	2.48	1.36	1.36	1.36	1.36	1.36
CO urban	g CO	2.48	1.36	1.36	1.36	1.36	1.36
PM10 total	mg PM10	380	272	272	272	272	272
PM10 urban	mg PM10	380	272	272	272	272	272
Energy Embodied	MJ LHV	0	0.000	0.000	0.000	0.000	0.000

4.12.3 Vehicle emissions - buses (g/km)

This section gives the calculated values for the emissions from buses, on a per-kilometre basis. The greenhouse gas emissions are graphed in Figure 4.10.

Table 4.31
Urban and total life cycle emissions per km for buses calculated for diesel and biodiesel

Full LC		LS Diesel	Canola biodiesel	Soybean biodiesel	Rape biodiesel	Tallow biodiesel	Tallow alternative allocation	Waste cooking oil biodiesel	Waste cooking oil alternative allocation
Greenhouse	kg CO_2	1.66	0.77	0.58	0.79	0.75	0.89	0.13	0.13
NMHC total	g HC	2.71	2.58	3.07	2.60	2.53	1.08	1.07	1.09
NMHC urban	g HC	2.14	2.39	2.91	2.39	2.33	1.06	1.05	1.07
NOx total	g NOx	20.20	23.15	22.94	23.48	23.08	21.16	21.12	21.21
NOx urban	g NOx	19.10	21.77	22.07	21.81	21.75	21.14	21.11	21.20
CO total	g CO	4.89	3.05	3.92	3.06	3.03	2.53	2.52	2.60
CO urban	g CO	4.69	2.77	3.75	2.78	2.76	2.52	2.51	2.60
PM10 total	mg PM10	787	534	525	545	533	493	493	493
PM10 urban	mg PM10	760	507	508	508	507	493	492	492
Energy Embodied	MJ LHV	22.8	7.4	8.1	7.6	7.3	3.0	2.9	3.0

Table 4.32
Urban and total precombustion emissions per km for buses calculated for diesel and biodiesel

Precombustion		LS Diesel (Aus)	Canola biodiesel	Soybean biodiesel	Rape biodiesel	Tallow biodiesel	Tallow alternative allocation	Waste cooking oil biodiesel	Waste cooking oil alternative allocation
Greenhouse	kg CO_2	0.37	0.77	0.58	0.79	0.75	0.89	0.13	0.13
NMHC total	g HC	1.09	2.51	3.00	2.53	2.46	1.01	1.00	1.02
NMHC urban	g HC	0.52	2.32	2.84	2.32	2.26	0.99	0.98	1.00
NOx total	g NOx	1.94	2.50	2.28	2.82	2.42	0.50	0.47	0.55
NOx urban	g NOx	0.84	1.11	1.41	1.15	1.09	0.48	0.45	0.54
CO total	g CO	0.44	0.62	1.49	0.63	0.60	0.09	0.08	0.17
CO urban	g CO	0.24	0.34	1.31	0.34	0.33	0.09	0.08	0.16
PM10 total	mg PM10	104.9	44.9	35.7	55.8	43.5	3.9	3.4	3.4
PM10 urban	mg PM10	77.4	18.1	19.0	18.7	17.5	3.7	3.2	3.2
Energy Embodied	MJ LHV	22.8	7.4	8.1	7.6	7.3	3.0	2.9	3.0

Table 4.33
Urban and total tailpipe emissions per km for buses calculated for diesel and biodiesel

Combustion		LS Diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow)	Biodiesel (waste cooking oil)
Greenhouse	kg CO_2	1.2910	0.0000	0.0000	0.0000	0.0000	0.0000
NMHC total	g HC	1.616	0.070	0.071	0.071	0.068	0.068
NMHC urban	g HC	1.616	0.070	0.071	0.071	0.068	0.068
NOx total	g NOx	18.270	20.658	20.658	20.658	20.658	20.658
NOx urban	g NOx	18.270	20.658	20.658	20.658	20.658	20.658
CO total	g CO	4.453	2.434	2.434	2.434	2.434	2.434
CO urban	g CO	4.453	2.434	2.434	2.434	2.434	2.434
PM10 total	mg PM10	682.3	489.2	489.2	489.2	489.2	489.2
PM10 urban	mg PM10	682.3	489.2	489.2	489.2	489.2	489.2
Energy Embodied	MJ LHV	0.00	0.00	0.00	0.00	0.00	0.00

4.12.4 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 4.34.

Table 4.34
Estimated one standard deviation uncertainties for biodiesel emissions

	g/MJ	g/t-km	g/p-km
CO2	15	15	7
NMHC	43	71	15
NOx	30	23	38
CO	72	106	37
PM10	71	81	61

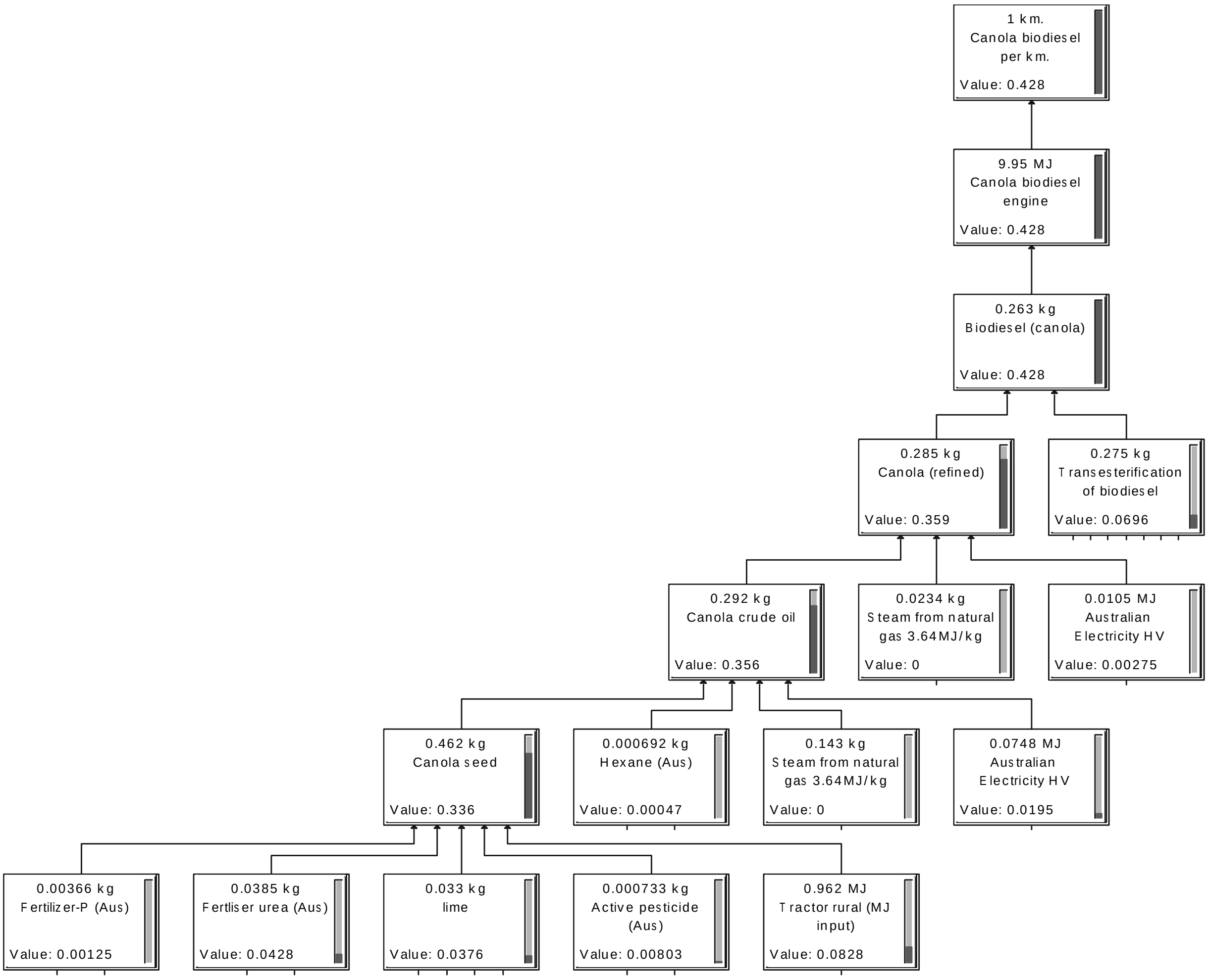

Figure 4.12
Exbodied greenhouse gas emissions (kg CO_2 eq) from canola biodiesel production and processing and use in vehicle (canola production expanded)

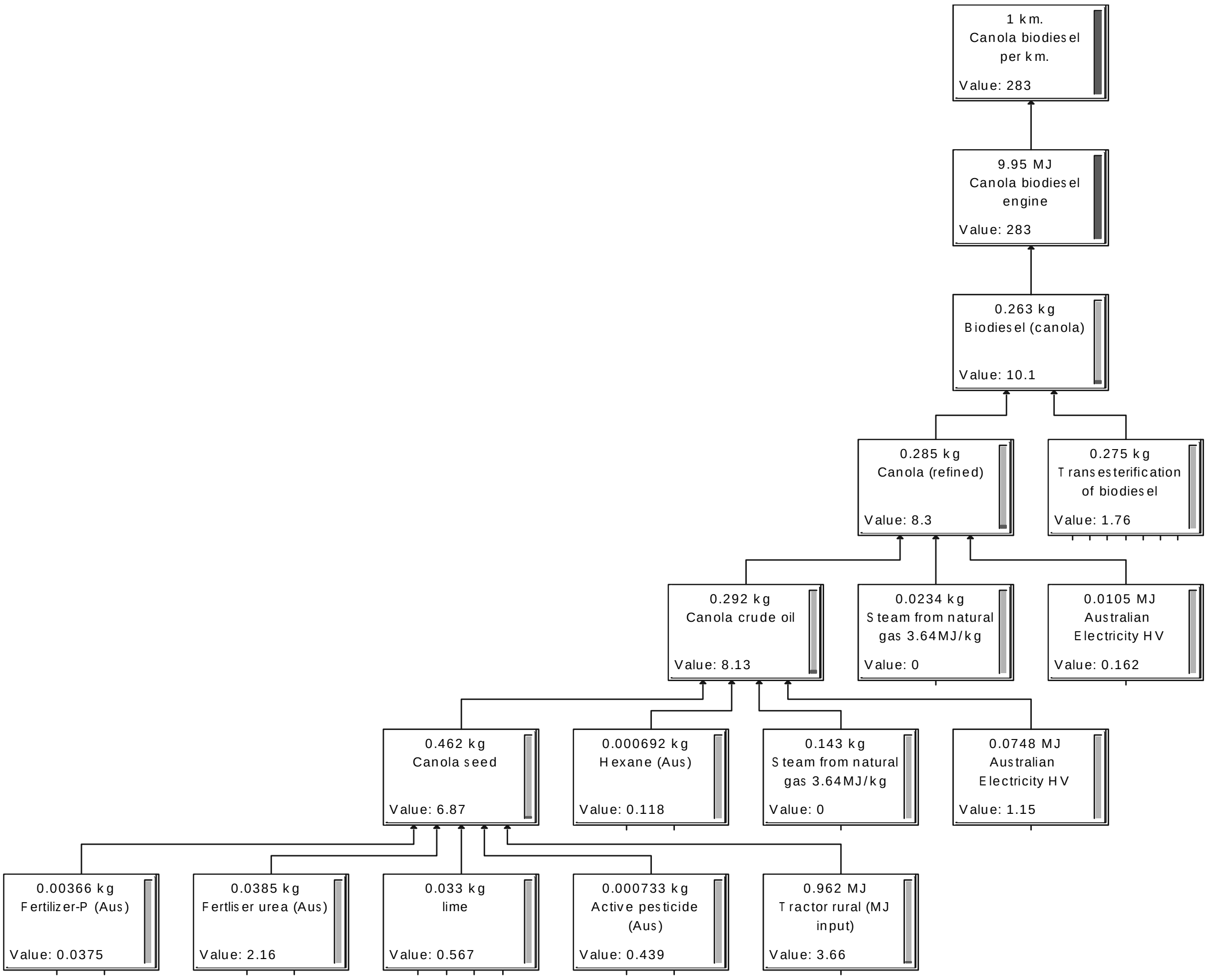

Figure 4.13
Exbodied particulate matter (mg - urban) from canola biodiesel production and processing and use in vehicle

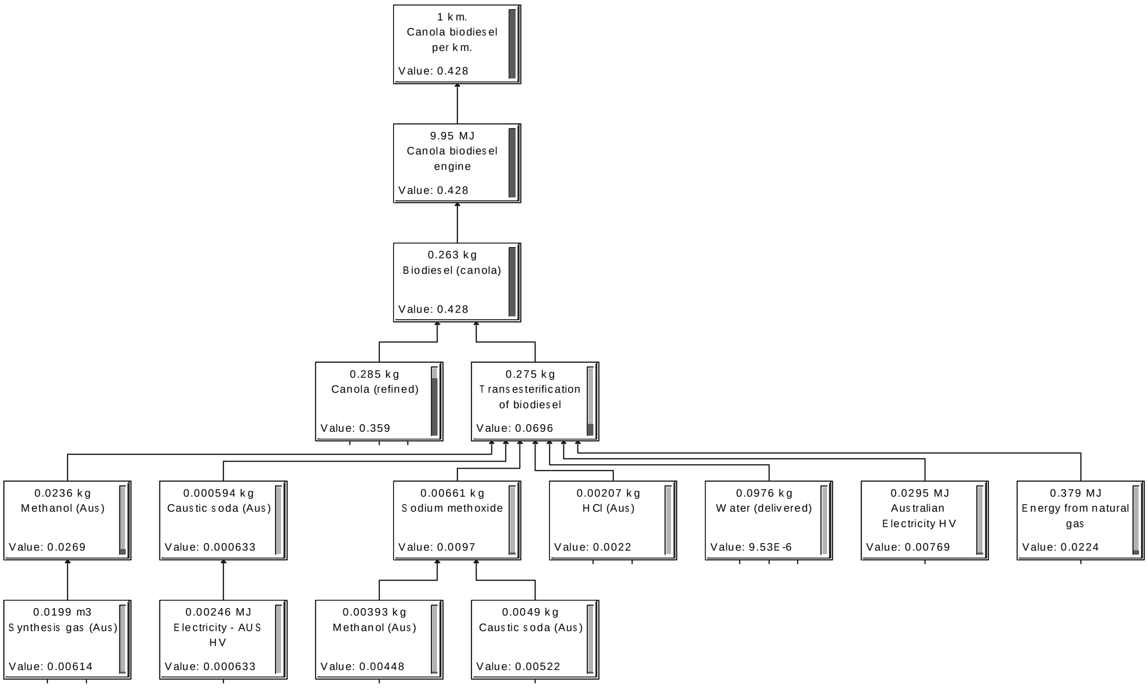

Figure 4.14
Exbodied greenhouse gas emissions (kg CO_2 eq) from canola biodiesel production and processing and use in vehicle (transesterification process expanded)

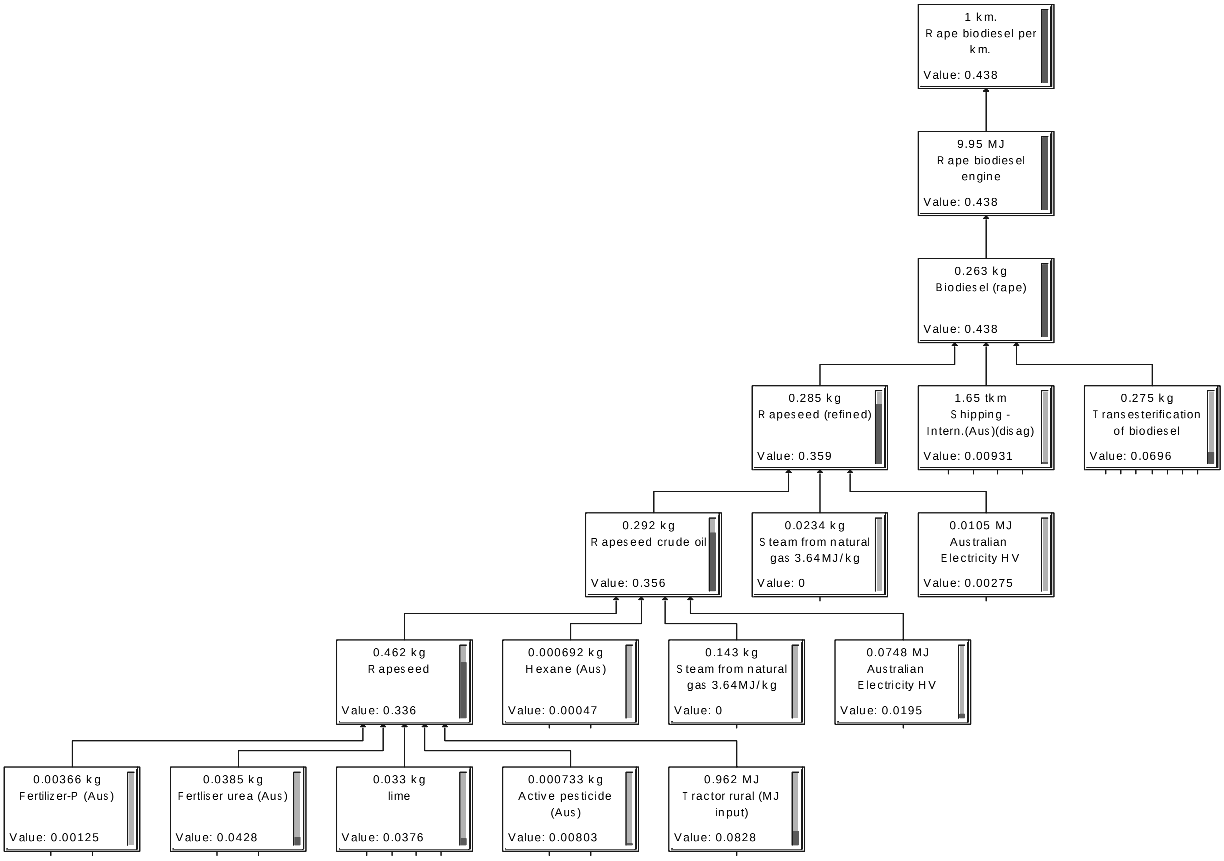

Figure 4.15
Exbodied greenhouse gas emissions (kg CO_2 eq) from rapeseed biodiesel production and processing and use in vehicle

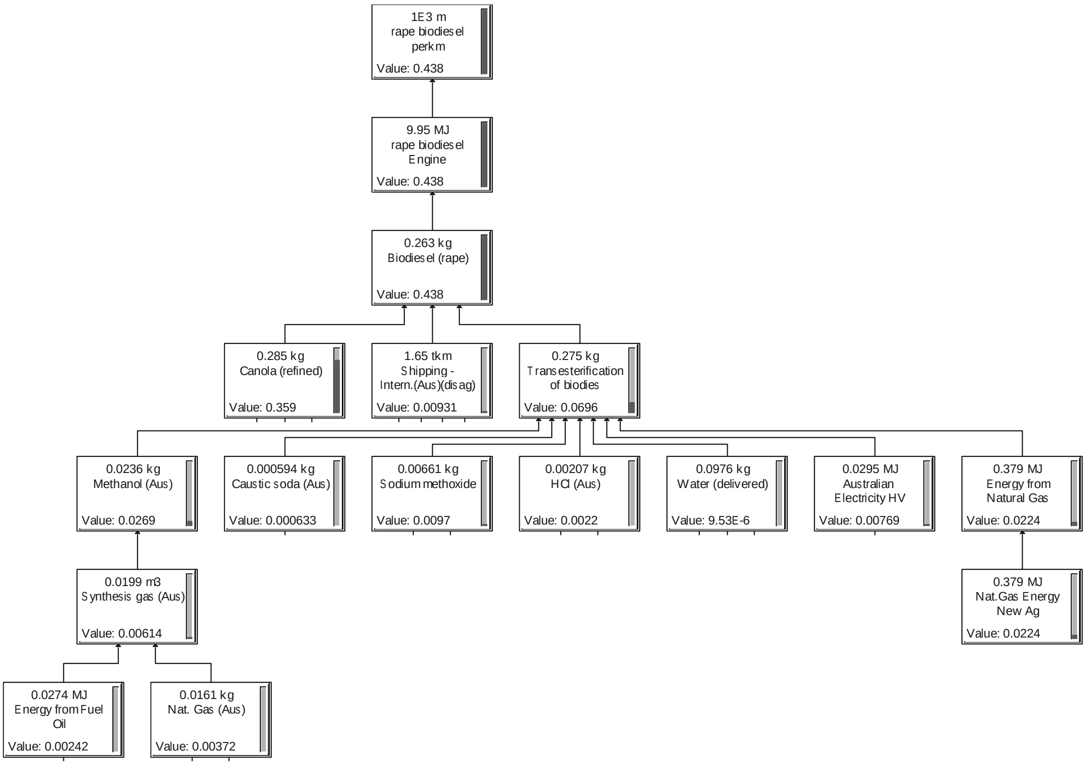

Figure 4.16
Exbodied greenhouse gas emissions (kg CO_2 eq) from rapeseed biodiesel transesterification

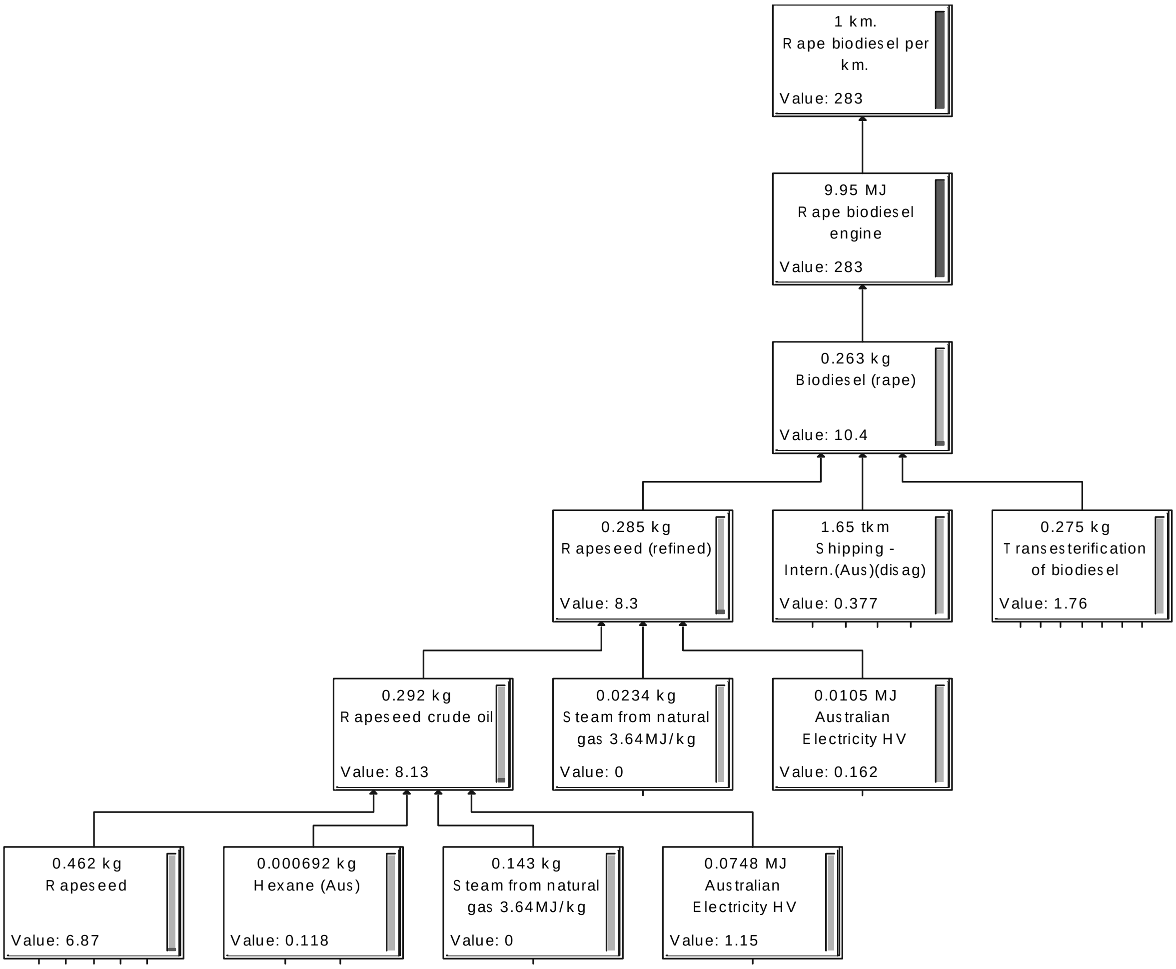

Figure 4.17
Exbodied particulate matter (mg - urban) from rapeseed biodiesel production, processing and use in vehicle

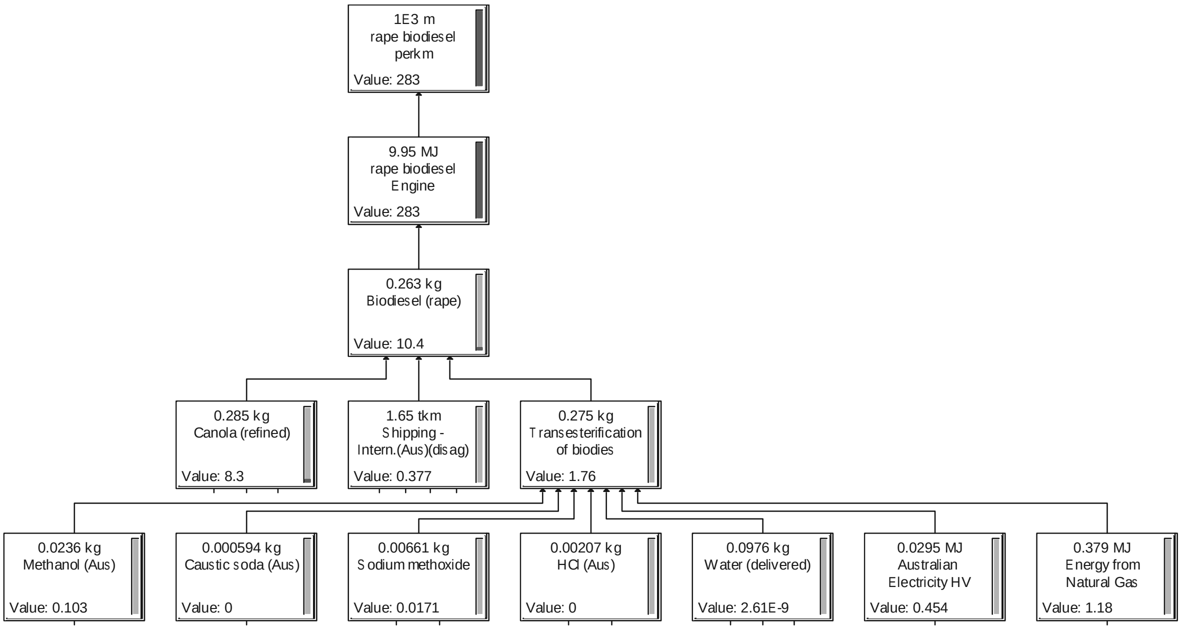

Figure 4.18
Exbodied particulate matter from rapeseed biodiesel transesterification

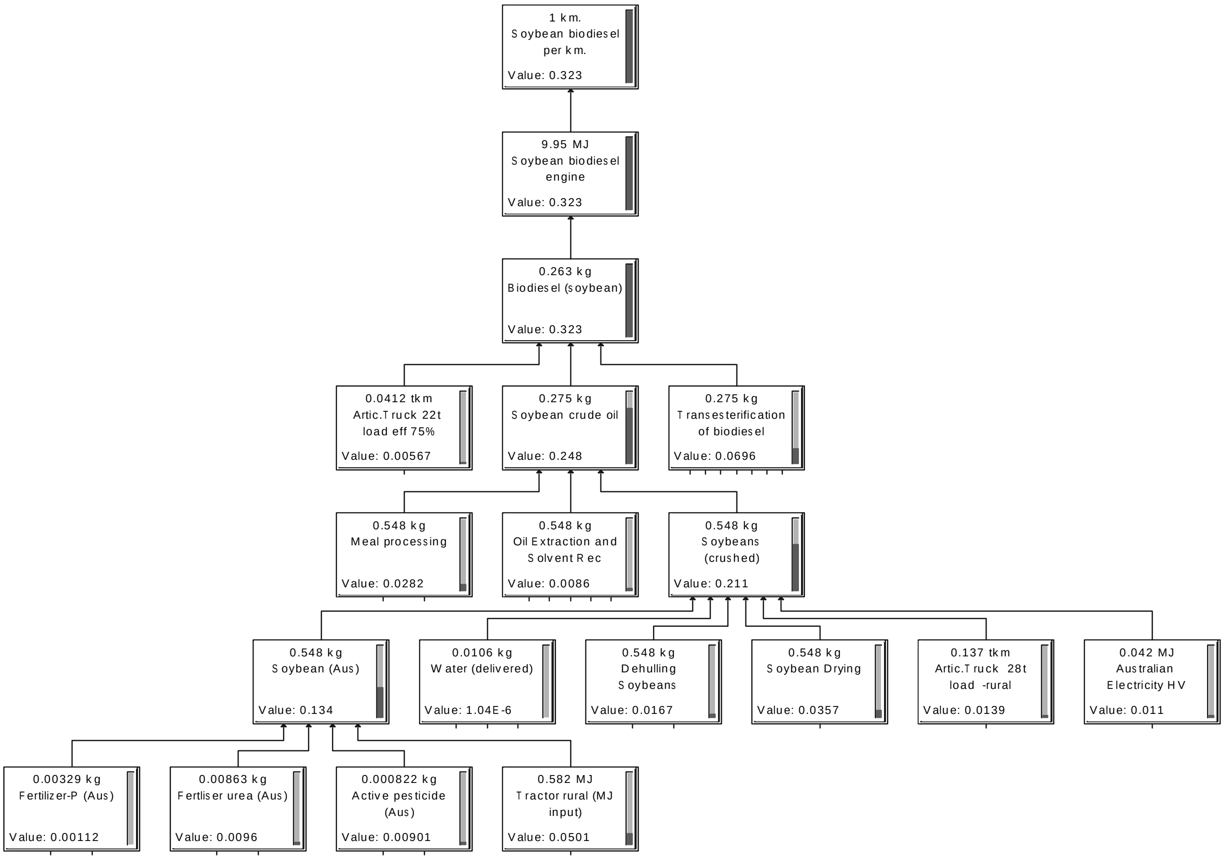

Figure 4.19
Exbodied greenhouse gas emissions (kg CO_2 eq) from soydiesel production, processing and use in vehicle

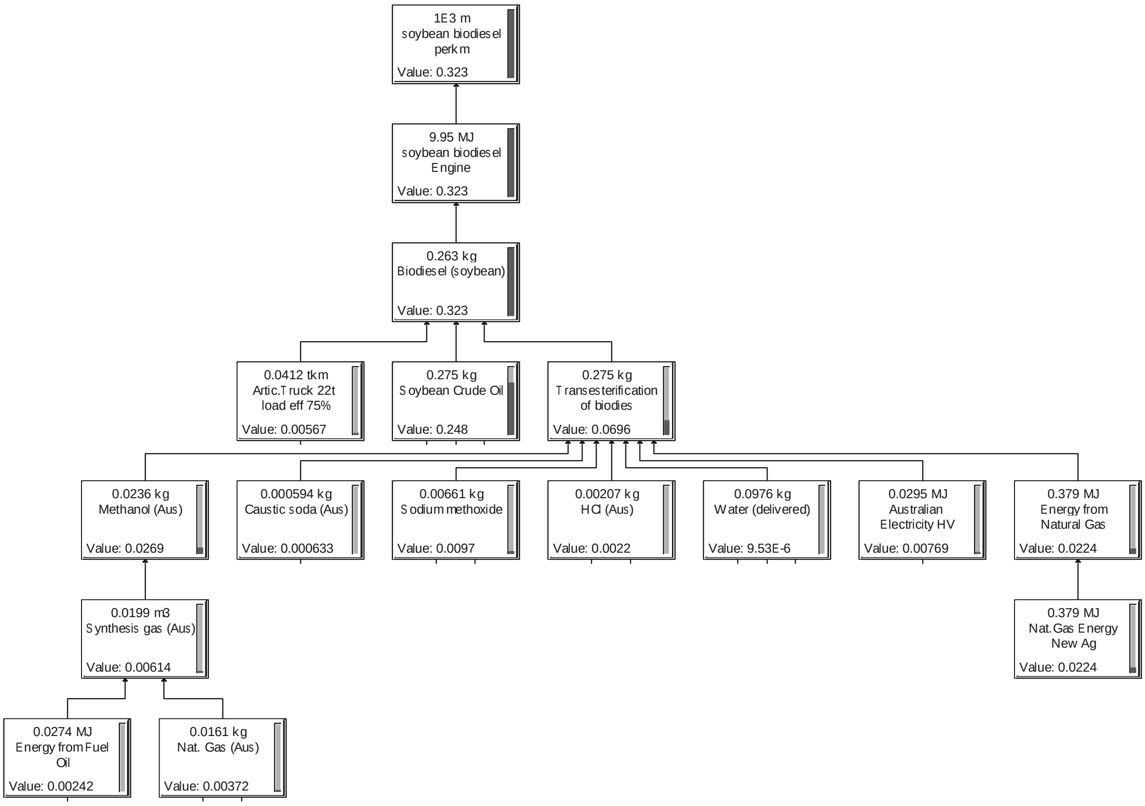

Figure 4.20
Exbodied greenhouse gas emissions (kg CO_2 eq) from soydiesel transesterification

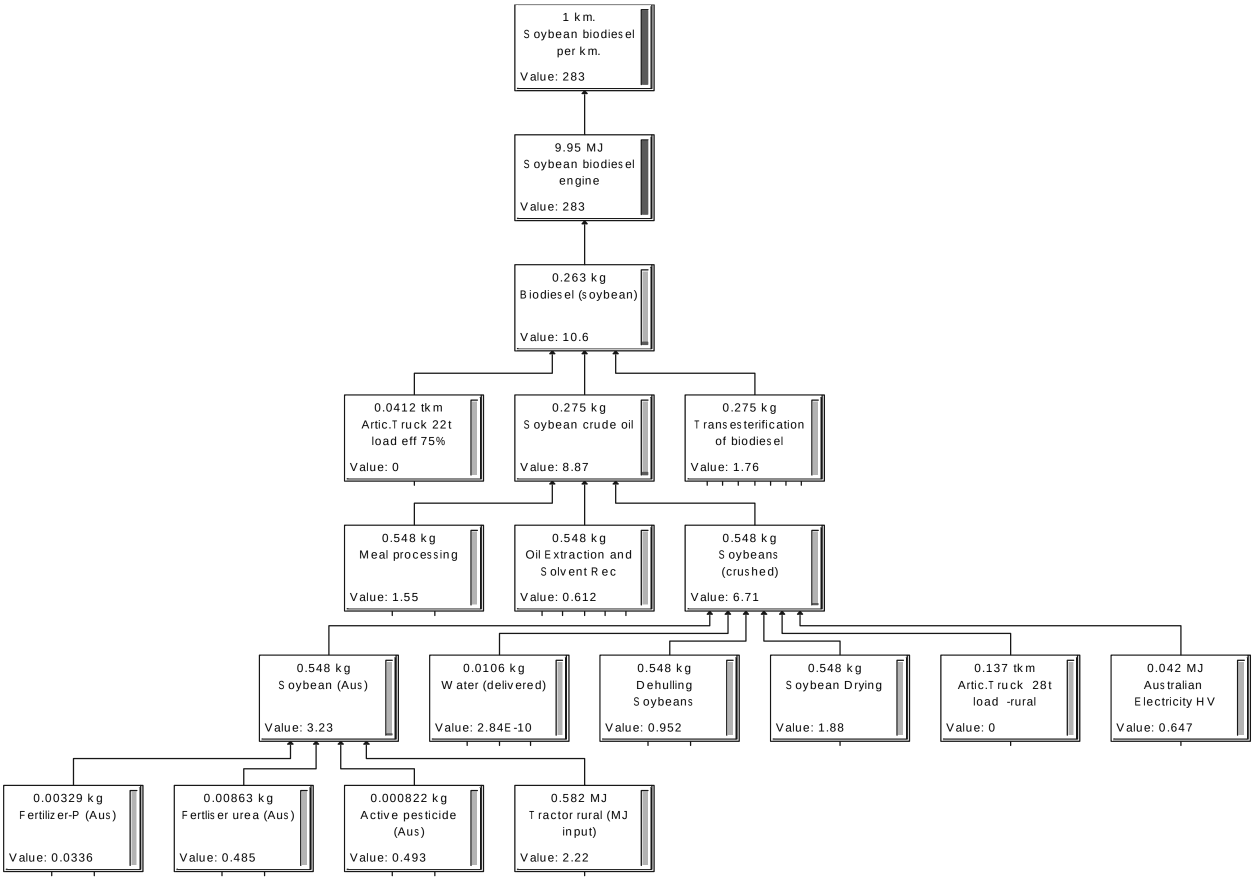

Figure 4.21
Exbodied particulate matter (mg - urban) from soydiesel production, processing and use in vehicle

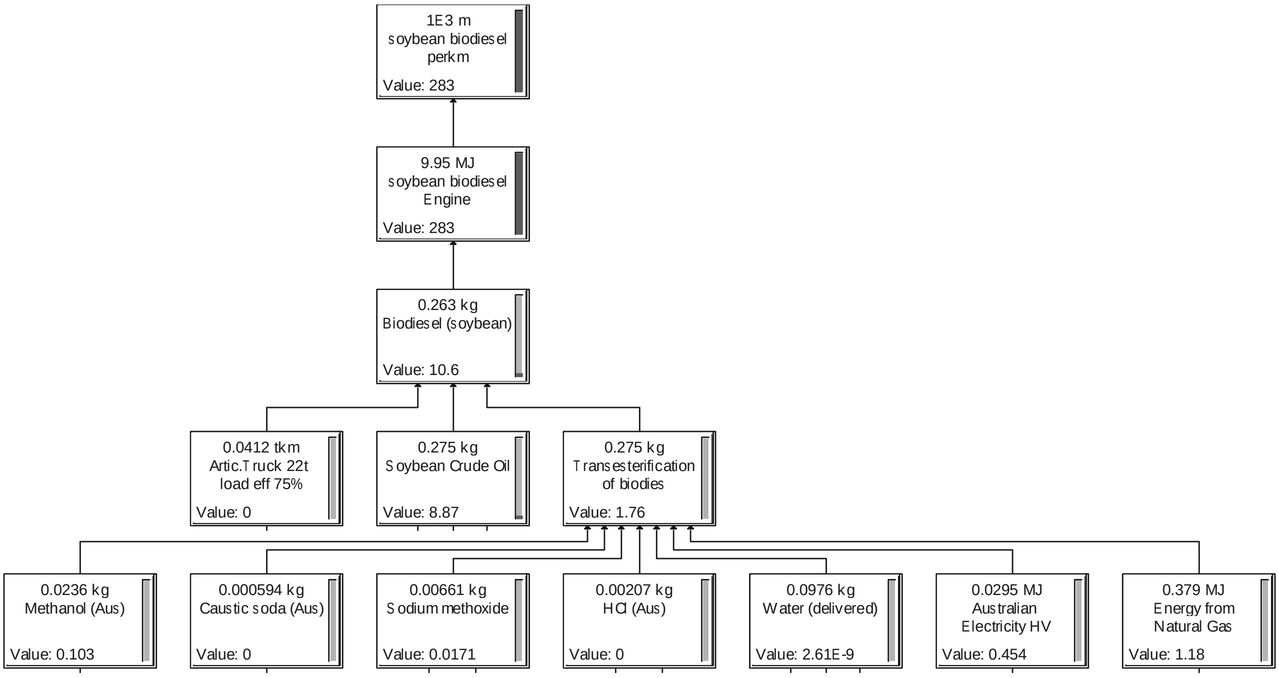

Figure 4.22
Exbodied particulate matter from soydiesel transesterification

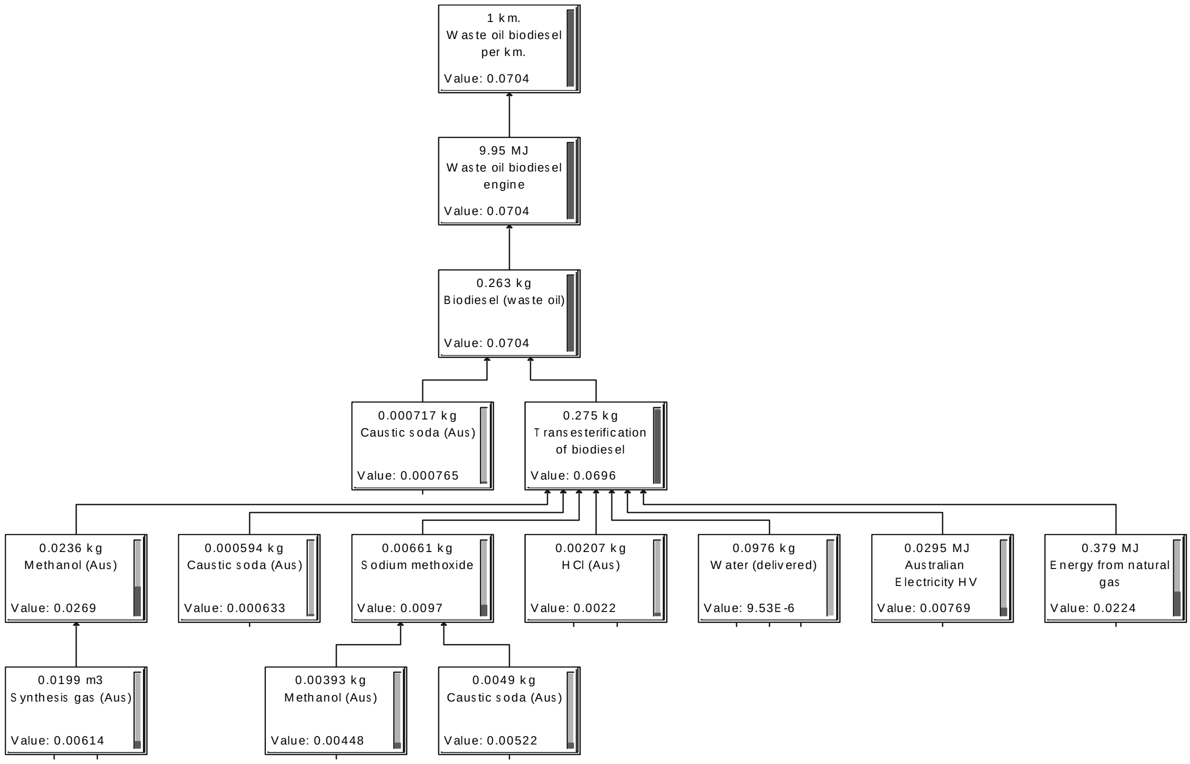

Figure 4.23
Exbodied greenhouse gas emissions (kg CO_2 eq) from McDiesel production, processing and use in vehicle

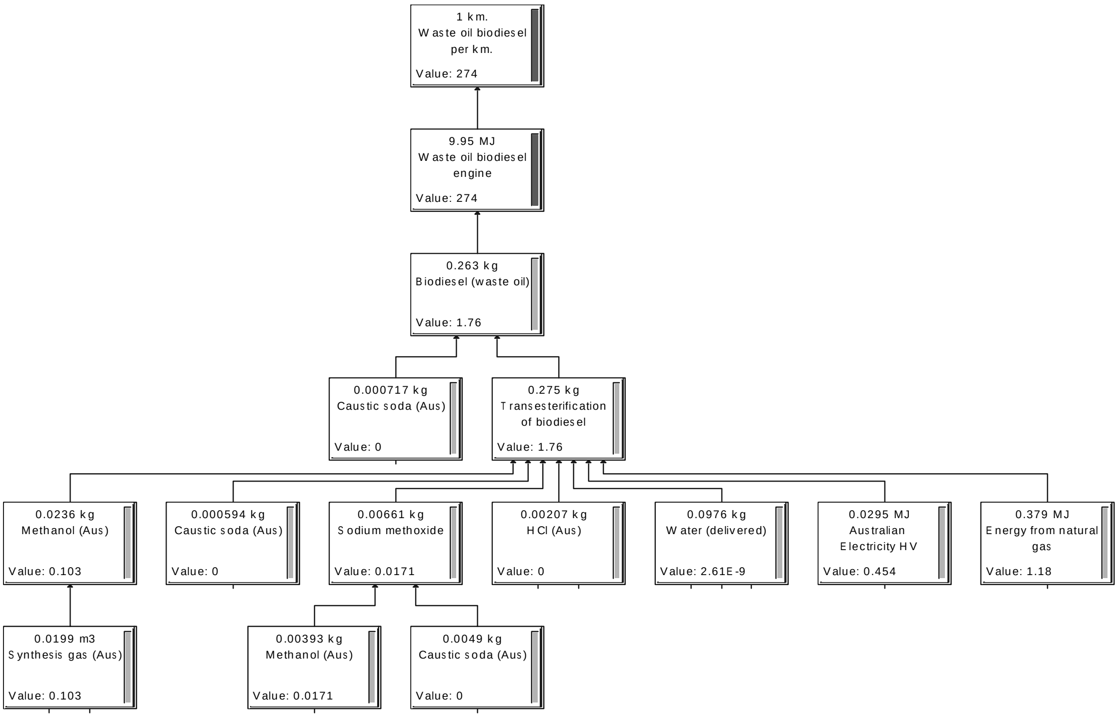

Figure 4.24
Exbodied particulate matter (mg - urban) from McDiesel production, processing and use in vehicle

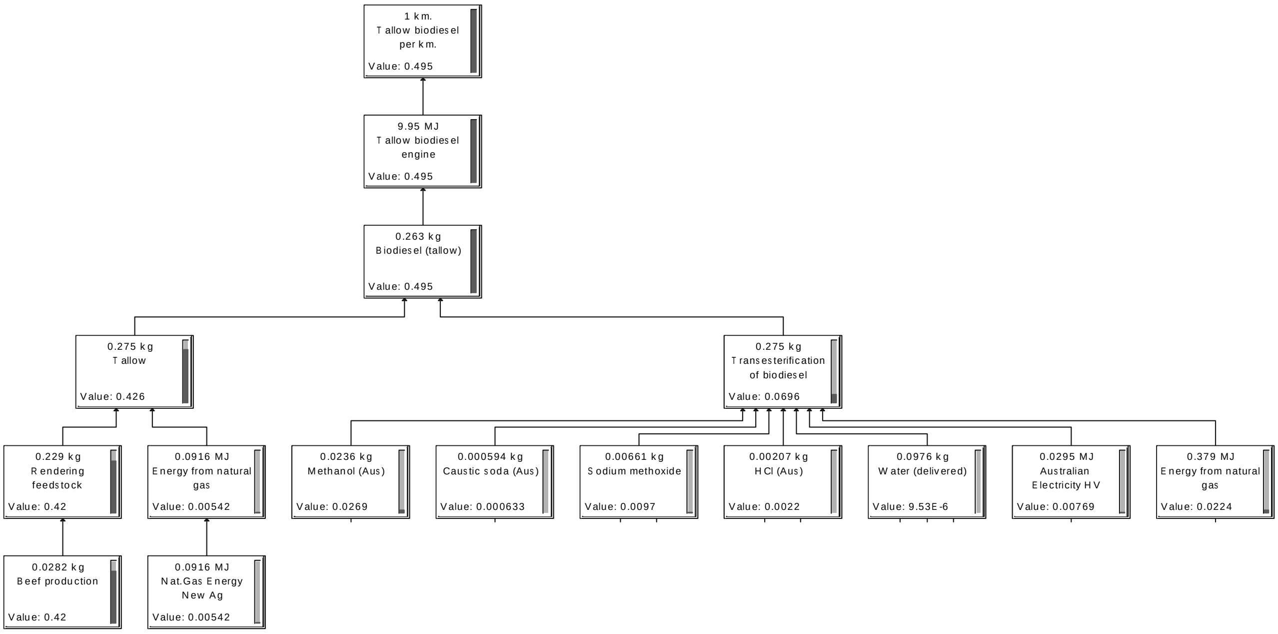

Figure 4.25
Exbodied greenhouse gas emissions (kg CO_2 eq) from Tallow-diesel production, processing and use in vehicle

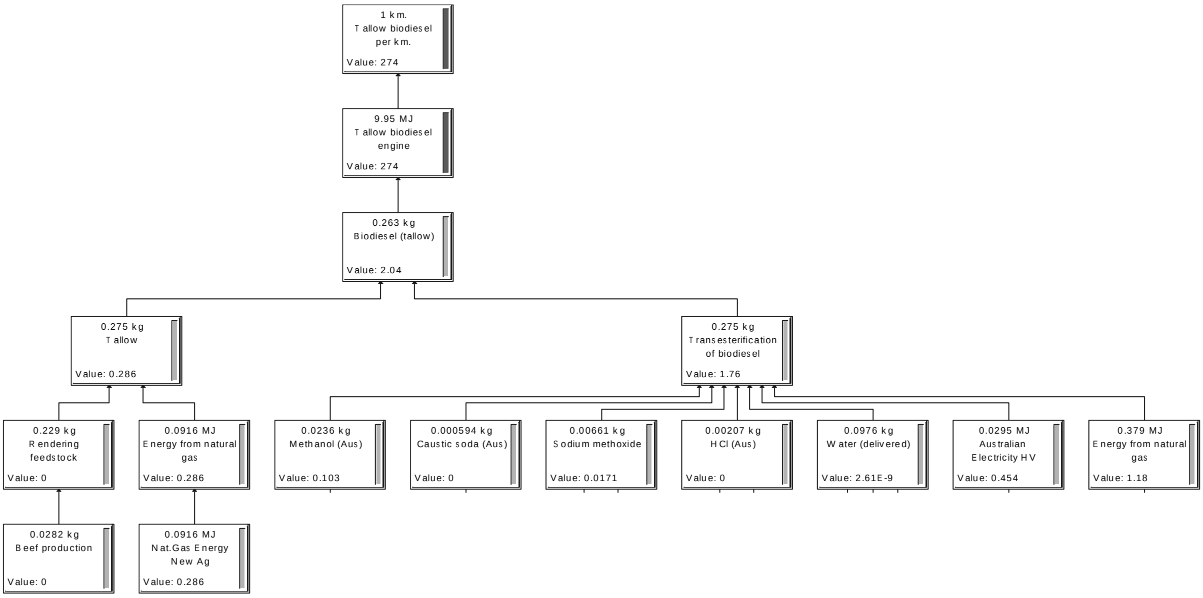

Figure 4.26
Exbodied particulate matter (mg - urban) from Tallow-diesel production, processing and use in vehicle

4.13. Viability, Functionality and Health Issues

European data (Arcoumanis, 2000) suggest biodiesel gives a reduction in HC compared with low sulfur diesel. CO tends to be lower for biodiesel. NOx tends to be slightly higher. PM may be lower (Buckmann & van Malsen, 1997) or it may be higher (Arcoumanis, 2000; Ceuterick & Spirinckx, 2000) but that is not clear. Within the variability and uncertainties associated with the fuels one should consider the particulate matter emissions of the two fuels to be much the same. The sulfur content of biodiesel is much lower than all grades of diesel.

United States LCA emissions estimates of BD100 compared to 500 ppm low sulfur diesel cited in Beer et al. (2000) found reductions for PM, CO and SOx by 32%, 35% and 8% respectively. BD100 increased LCA NOx emissions by 13% due mainly to increased tailpipe emissions. LCA HC emissions for BD100 are 35% higher with most of this increase due to soybean farming and production (soybean was the feedstock assessed), while tailpipe HC are 37% lower than diesel. Tailpipe emissions of PM10 and CO were substantially reduced by 68% and 46% respectively on a g/km basis.

The British Association for Bio Fuels and Oils (BABFO) summarised the life cycle emissions of gaseous pollutants from diesel and biodiesel for the UK (EcoTec Research and Consulting Ltd, 1999). Their results are summarised in Table 4.24. The relative differences between diesel and biodiesel confirm some of the earlier findings – in particular the larger full fuel-cycle emissions of particulate matter from biodiesel when compared to diesel although this may be different when compared with LSD which generally has lower PM emissions.

There are discrepancies between biodiesel emissions results emanating from Europe and the United States. Discrepancies in the PM emissions between studies may be related to whether the engine was optimised to run on biodiesel or diesel.

The influence of biodiesel fuels including rapeseed oil fuels on the formation of photochemical smog, whose main component is ozone, may be inferred from the fact that ozone in Australian cities is mainly NOx limited. The addition of extra NOx (from biodiesel compared to the NOx emissions from diesel) would thus slightly increase the smog production propensity.

The LCA biodiesel results from the earlier Stage 1 report are given in Table 8.9 of Beer et al. (2000).

4.13.1 Production and transport

Production of the canola, rapeseed and soybean feedstock crops would result in a range of particles and VOC from various sources including farm and transport vehicle emissions, plant respiration, agricultural chemicals and fertilisers. Feedstock transport to the vegetable oil processing facilities and vegetable oil transport to the esterification processing facility would also result in a range of particle and VOC emissions.

Particulate matter

The results summarised in Table 4.29 indicate that the upstream PM emissions from biodiesel are less than for LSD. This differs from the earlier analysis of Beer et al. (2000) as a result of using updated emission factors for agricultural machinery.

Air toxics

An accompanying disk to this report provides details of air toxics emissions from upstream activities.

4.13.2 Use

Taberski et al. (1999) looked at the biodiesel emissions when using rapeseed ethyl ester (REE) blends in a 1995 Dodge 2500 four-wheel-drive pickup truck with a Cummins B 5.9 litre turbocharged direct injection diesel engine with and without a catalytic converter. They found that REE100%:

- Reduced CO emissions by 40% (the catalytic converter had little effect).
- Reduced NOx emissions by 10% (the catalytic converter had little effect).
- Reduced HC emissions by 60% (the catalytic converter had little effect).
- Increased PM emissions by 15% and 40% with and without a catalytic converter respectively.

Engine dynamometer tests by Sharp et al. (2000a) found:

- With neat biodiesel, measurable HC emissions were generally eliminated, while CO was reduced roughly 40% from levels found in low sulfur diesel (2D diesel).
- Particle emissions were reduced between 25 and 50%, depending on the engine. In addition, the composition of engine-out particulate matter was shifted toward more volatile organic compounds and less carbon soot, creating a more favourable environment for treatment by a diesel oxidation catalyst.
- Neat biodiesel generally tended to increase NOx emissions by roughly 12%, although the Cummins B5.9 engine demonstrated almost no change in NOx emissions.

Particulate matter

We have noted that the particulate matter emission from biodiesel combustion is variable, with some studies indicating higher emissions than from diesel and some studies indicating lower emissions than from diesel. Consultation with stakeholders indicated that the Tier 1 test results (Sharp, 1998) – conducted on an engine dynamometer - have widespread credibility and thus these were used in the analysis. The particulate matter emissions during combustion of biodiesel are thus approximately 20% below those emitted during combustion of low sulfur diesel.

Air toxics

Sharp (1998) also conducted a detailed characterisation of the exhaust components. Unregulated emissions were characterised with neat biodiesel and conventional diesel fuel. This characterisation included several forms of hydrocarbon speciation, as well as measurement of aldehydes, ketones, and alcohols. In addition, both particle-phase and semi-volatile-phase PAH and nitro-PAH compounds were measured. Chemical characterisation revealed lower levels of most toxic and reactive hydrocarbon species when biodiesel fuels were used. Increases were observed only in heptane, acrolein, propionaldehyde, and hexanaldehyde, but the increases (except for heptane, which is not considered to be an air toxic) were small.

In addition, emissions of PAH and nitro-PAH compounds were substantially lower (30% with a catalytic converter, 12% without a catalytic converter) with biodiesel, as compared to conventional diesel fuel.

There are reduced emissions of speciated vapour phase hydrocarbons in the C1 to C12 range. The relative reactivity of speciated hydrocarbons with biodiesel was similar to that observed with diesel exhaust hydrocarbons, although the lower mass of speciated hydrocarbons present with biodiesel resulted in a lower overall ozone potential than for speciated diesel hydrocarbons.

Biodiesel reduced emissions of aldehydes and ketones substantially.

Biodiesel caused large reductions in PAH and NPAH emissions as already noted, and virtually eliminated some of the heavier NPAH compounds in the exhaust.

Biodiesel caused a dramatic change in the character of the heavier HC species as compared to diesel fuel, with only the esters that made up the biodiesel remaining in exhaust among the higher molecular weight hydrocarbons.

The blending of biodiesel and diesel did not generate any new species not already present in diesel or biodiesel exhaust.

A study by Pedersen et al. (1999) investigated emissions of rapeseed oil and RME burnt in a laboratory reactor. The study found combustion of rapeseed oil and RME resulted in emissions or a range of VOC including 1,3 butadiene, benzene and alkenes. The USEPA considers acrolein to be a high concern pollutant based on acute chronic toxicity. The USEPA classifies acrolein as a Group C, possible human carcinogen. The authors acknowledge that the results need to be checked using engines running RME. The Tier 1 results of Sharp (1998, Table 4.5), indicate that the acrolein emissions are small and seem to be compensated by the decrease in formaldehyde and acetaldehyde.

It is difficult to compare the combustion emissions of substantially different fuels such as LSD and biodiesel. The Taberski et al. (1999) data estimate the HC ratio of REE to diesel of 0.38. This is very different to the ratio of 1.68 between biodiesel HC and LSD found by Beer et al. (2000: Table 3.1) or the value of about 0.04 found in this study. As noted in Table 4.7, studies consistently find that biodiesel emits less hydrocarbons than diesel, so that a ratio of less than 1 appears to be reasonable.

4.13.3 Biodiesel emissions summary

Combustion PM emissions from biodiesel are comparable to those from diesel. This study has used the Tier 1 results of Sharp (1998) that found lower PM emissions from biodiesel than from diesel.

It is not possible to estimate robust combustion emissions estimates from the identified biodiesel toxics data. The Tier 2 results (Lovelace Respiratory Research Institute, 2000) for biodiesel found, in a study of health effects in rats, no effects associated with air toxic emissions from biodiesel with respect to mortality, toxicity, fertility or teratology. Rats lungs were adversely affected by exposure to high-level biodiesel exhaust emissions. This was judged to be a normal physiological response to exposure and not a toxic reaction.

4.13.4 OHS Issues

The Biodiesel Association of Australia provides a sample material data safety sheet (MSDS) for biodiesel on its web site at www.biodiesel.vtrekker.com/biodiesel.htm that identifies mucous membrane irritation from biodiesel vapours, and eye irritation from direct contact as the only hazards. This is more conservative than the MSDS for soydiesel (methyl soyate) at www.soygold.com/soydiesel-msds.htm, which claims that soydiesel is not classified as an eye irritant.

A range of State and Commonwealth occupational health and safety provisions covers the OHS issues in the lifecycle of biodiesel. While there will be different OHS issues involved in the production process associated with biodiesel compared with LSD, no OHS issues unique to the production and distribution of biodiesel have been identified, provided that normal industrial precautions are followed in the use of the ingredients needed to prepare the biodiesel.

4.13.5 Vapour pressure issues

There are minimal evaporative emission issues during the transport and use of biodiesel due to the relatively low volatility of biodiesel. The soydiesel MSDS claims that the vapour pressure is less than 1 mm of mercury (133 Pa) at 72°C.

4.13.6 Warranty issues

The Austrian Biofuels Institute provided a list of existing European warranties for biodiesel operation that is reproduced in Table 4.35. Our understanding is that these warranties relate to the use of BD100, which is readily available in parts of Europe at a cheaper price than diesel fuel.

According to the summary at www.biodiesel.org/fleets/summary.htm, the biodiesel industry in the United States is working with the Engine Manufactures Association as well as with individual firms to address many of the OEMs' issues and concerns (see below) over biodiesel use. They state that a common misconception is that an engine manufacturer must warranty biodiesel in order to use it in the United States. The reality is that no engine manufacturer warranties any fuel, because they do not produce fuel. If there is a problem caused by the fuel, it is the responsibility of the fuel supplier.

Engine manufacturers do, however, warranty the materials and workmanship of their engines and have the ability to void their materials and workmanship warranties if certain fuels are used in their engines. The question for biodiesel use is whether the use of biodiesel will void their existing warranty. Almost all the companies marketing diesel engines in the United States have confirmed that the use of BD20 will not void their parts and materials warranties. This allows BD20 to be used in most existing engines with no further approvals.

Caterpillar, in its Information Release Memo PMP01-01 of March 2001 states that Caterpillar neither approves nor prohibits the use of biodiesel fuels. The memo lists 23 engines in which biodiesel meeting either ASTM PS 121 or DIN 51606 are acceptable, and notes that for Caterpillar 3003 through 3034, 3054 and 3056 engines use of more than a 5% biodiesel fuel can cause premature failures whose repair would not be covered under Caterpillar warranty.

The information that we received from stakeholders during consultations is that in Australia there is concern at biodiesel blends above 5% (BD5). Fuel Injection Equipment (FIE) Manufacturers (Bosch, Stanadyne, Lucas) issued a joint statement dated 1 May 1998 that states that BD5 "should not give end-users any serious problems". The statement does, however, express concern about possible interaction between the fuels and components in the vehicle low pressure system. The intent of the statement is to inform potential users that if problems arise following the use of biodiesel above a 5% blend, or following the use of a biodiesel that does not meet a national standard, then this will render the FIE manufacturers' guarantee null and void.

The Cummins position on biodiesel states that:

> Cummins neither approves nor disapproves of the use of biodiesel fuel blends. There is a major difference between operating on pure (100% concentration) bio diesel fuels and biodiesel/petrodiesel fuel blends. Cummins is not in a position to evaluate the many variations of biodiesel fuels, and the long-term effects on performance, durability or emissions compliance of Cummins products. The use of biodiesel fuel does not affect Cummins materials and workmanship warranty. Failures caused by the use of biodiesel fuels or other fuel additives are not defects of Cummins parts or workmanship, and therefore would NOT be covered by Cummins' warranty.

> Given the current industry understanding of biofuels and blending with quality diesel fuel, it would be expected that blending up to a 5% volume concentration should not cause serious problems. This is consistent with the position taken by worldwide fuel system manufacturers.

Table 4.35
Summary of existing diesel vehicle warranties for biodiesel operation

Audi	personal cars	all TDI-models since 1996
Case – IH	Tractors	all models since 1971
BMW	personal cars	model 525 tds since 1997
Claas	combines, tractors	warranties exist
Faryman Diesel	Engines	warranties exist
Fiatagri	Tractors	for new models
Ford AG	tractors	for new models
Holder	tractors	warranties exist
Iseki	tractors	series 3000 and 5000
John Deere	tractors	warranties since 1987
John Deere	combines	warranties since 1987
KHD	tractors	warranties exist
Kubota	tractors	series OC, Super Mini, O5, O3,
Lamborghini	tractors	series 1000
Mercedes-Benz	personal cars	series C and E 220, C 200 and 220 CDI, a.o.
Mercedes-Benz	lorry, bus	series BR 300, 400, Unimog since 1988, a.o.
Mercedes-Benz	tractors	since 1989
Same	tractors	since 1990
Seat, Skoda	personal cars	all TDI-series since 1996
Steyr	tractors	since 1988
Steyr	boat	series M 16 TCAM and M 14 TCAM
Valmet	tractors	since 1991
Volkswagen	personal cars	all TDI- series since 1996
Volkswagen	personal cars	all new SDI-series (EURO-3)
Volvo	personal cars	series S80-D, S70-TDI and V70-TDI

(Provided by Austrian Biofuels Institute)

At present few engine manufacturers have certified BD100 due to the added costs involved with certification and lack of data using BD100, since almost all the research in the United States has been on BD20. The National Biodiesel Board is currently leading an industry wide effort to have BD20 designated as an alternative fuel by the US Department of Energy. Successful designation of BD20 will provide a blend level with which both Original Equipment Manufacturers (OEMs) as well as other third parties (after market converters, fuel suppliers, etc.) can certify cost competitive biodiesel blends.

4.13.7 Other issues

The National Biodiesel Board web site also points out that biodiesel over time will soften and degrade certain types of elastomers and natural rubber compounds. Precautions are needed when using high percentage blends to ensure that the existing fuelling system, primarily fuel hoses and fuel pump seals, do not contain elastomer compounds incompatible with biodiesel. Manufacturers recommend that natural or butyl rubbers not be allowed to come in contact with neat biodiesel. Biodiesel will lead to degradation of these materials. If a vehicle's fuel system does contain these materials, replacement with biodiesel compatible elastomers such as Viton® B is recommended. The recent switch to low sulfur diesel fuel has caused most (OEMs) to switch to components suitable for use with biodiesel, but users should contact their OEM for specific information. (Viton B is a registered trademark of DuPont Dow Elastomers). The FIE manufacturers' position statement on Fatty Acid Methyl Esters of 1 May 1998 also makes similar points and provides a list of potential fuel injection problems.

The Cummins position on the use of biodiesel fuel notes that:

> For customers intent on blending bio fuels above a 5% volume concentration, the following concerns represent what is currently known in the industry. Concentrations beyond 5% by volume could have an adverse effect on the engine's performance and the fuel system integrity/durability. The effects are more serious with increasing concentration levels. Areas of concern when operating with bio diesel fuels include low temperature operability (fuel gelation, filter plugging), heat content (poor fuel economy), and storage and thermal stability (filter plugging, injector deposits). In addition, from our fuel systems suppliers, the following issues are also noted: swelling and hardening/cracking of some elastomer seals within the fuel system/engine, corrosion of fuel system and engine hardware - especially aluminum and zinc, solid particle blockage of fuel nozzles and passages, filter plugging, injector coking, higher injection pressures due to physical flow properties - reduced fuel system life, added stress and heat to injection components - especially rotary fuel pumps – increased pump seizures and early life failures, poor fuel spray atomization - reduced fuel economy, poor lubricity - reduced service life of fuel pump/system. Pure bio diesel fuel is not stable and its acid content increases over time, which can damage powder metal components.

In contrast to the cautious attitude of the manufacturers, the major case study that we were able to find on the long-term use of biodiesel was the "truck in the park" project detailed by Taberski et al. (1999). This project examined the performance of a new 1995 Dodge pickup truck with a Cummins B5.9 litre turbocharged, direct injected, diesel engine over three years, from 1995 to 1998, using biodiesel. On-road fuel for the truck was 100% canola ethyl ester, whereas during dynamometer testing the fuel used was 100% rapeseed ethyl ester. The performance of the biodiesel fuelled truck was compared with that of a control vehicle running on low sulfur diesel.

Neither the "truck in the park" project, nor the other road-test projects run by the University of Idaho (http://www.uidaho.edu/bae/biodiesel/research/past_research.html) found any difference in engine viability and functionality between diesel and biodiesel.

4.13.8 Cold flow properties

Operation of neat (100%) biodiesel in cold weather will experience gelling faster than petrodiesel. The solutions for this potential issue are much the same as that with low-sulfur diesel (i.e., utilisation of fuel heaters and storage of the vehicle in or near a building). Biodiesel appears to be largely unaffected by conventional pour point depressants. These considerations, though important in the United States, are not relevant to most of Australia.

4.13.9 Summary

The advantages of biodiesel are:

- It is a renewable bio-based fuel and, as such, has lower life cycle CO_2 emissions than diesel derived from mineral oils.
- Neat biodiesel contains almost no sulfur and no aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The material is bio-degradable and non-toxic.
- As an oxygenated compound, it reduces the non-soluble fraction of the particles.
- The PAH content of exhaust particles is reduced.
- In a mixture with low-sulfur diesel, biodiesel can act as a lubricity improver (Arcoumanis, 2000).
- The absence of sulfur makes oxidation catalysts more efficient.
- Existing diesel infrastructure could be converted to use biodiesel.
- Biodiesel can be used in existing diesel engines.

The disadvantages of biodiesel are:

- Constraints on the availability of agricultural feedstock impose limits on the possible contribution of biodiesels to transport.
- The kinematic viscosity is higher than diesel fuel. This affects fuel atomisation during injection and may require changes to the fuel injection system.
- Due to the high oxygen content, it produces relatively high NOx levels during combustion.
- Oxidation stability is lower than that of diesel so that under extended storage conditions it is possible to produce oxidation products that may be harmful to the vehicle components.
- Biodiesel is hygroscopic. Contact with humid air must be avoided.
- Production of biodiesel is not sufficiently standardised. Biodiesel that is outside European or US standards can cause corrosion, fuel system blockage, seal failures, filter clogging and deposits at injection pumps.
- There is a possibility of dilution of engine lubricant oil, requiring more frequent oil change than in standard diesel-fuelled engines.
- A modified refuelling infrastructure is needed to handle biodiesels, which adds to their total cost.

4.14. Environmental Issues

Biodiesel is made from agricultural crops and is thus widely perceived to be more environmentally friendly than fossil fuels. It is presented as such by the biodiesel industry. Biodiesel International is an Austrian company that is a leader in developing multi-feedstock facilities for the production of high-quality biodiesel. The company's home page at www.biodiesel-intl.com has pictures of birds with the motto: "a bird in clean air gliding over healthy soil". This emphasises that spillages of biodiesel are less toxic than spillages of crude oil or diesel. There is less likelihood of soil contamination, and the chances of groundwater contamination are greatly reduced.

When examined on a total life cycle basis it remains unclear whether the planting of large scale crops to be used for biodiesel is to be seen as a positive contribution to sustainability or as a contributor to soil degradation. Such analyses are local in scale and need to be determined for individual projects on the basis of the use of the land before fuel crop cultivation.

Crops in Australia require application of fertiliser and pesticides to be grown successfully. There are concerns as to whether such agricultural practices are sustainable. However, there are also concerns at the alternatives. Australian farms have experimented with genetically modified canola so as to reduce the amount of pesticide applied. There is sufficient community concern over the risks associated with genetically modified organisms (GMO) that in late 20000, the Commonwealth established an Office of the Gene Technology Regulator.

The main focus of environmental issues related to biodiesel has been that of air emissions (Franke and Reinhardt, 1998). These have been dealt with in earlier sections. We may summarise the environmental issues as follows:

4.14.1 ESD issues

The present use of biodiesel is that of a niche fuel. As such, there are no issues related to sustainability.

Biodiesel is made from agricultural crops and is thus widely perceived to be more environmentally friendly and ecologically sustainable than fossil fuels. Our results confirm that, on a life-cycle basis, biodiesel is more climate-friendly than diesel. Vegetable crops much more so than biodiesel made from tallow. The carbon emissions caused by agricultural production and fertiliser production are less than the exbodied emissions from diesel made from fossil fuels.

4.14.2 Sustainability issues

Biodiesel is made from either crops or from animal product. Its feedstock is thus a renewable resource. It is less clear whether the high levels of pesticides and fertiliser necessary to conduct present-day agricultural activities are sustainable within the Australian context. Biodiesel will be a niche fuel, albeit a very useful one, because there is not sufficient area to grow the plants needed to convert all of Australia’s diesel fuel usage to biodiesel.

4.14.3 Groundwater contamination

Not an issue with biodiesel, except for i) the possible use of pesticides or fertiliser during the growth of the crop from which the biodiesel is made, and ii) runoff from cattle feedlots (for biodiesel made from tallow).

4.15. Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 4.36
Estimated relative emission factors for biodiesel under different technologies.
Euro2 diesel values (shown in bold) are taken as 1.0.

Technology	CO	CO	HC	HC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.7	**1.0**	0.4	**1.0**	1.1	**1.0**	1.0	1.1	0.1-0.3
Euro3	**0.53**	0.4	**0.6**	0.3	**0.71**	0.9	**0.67**	0.7	1.1	0.1-0.3
Euro4	**0.38**	0.3	**0.42**	0.2	**0.5**	0.6	**0.2**	0.2	1.0	0.1-0.3

Table 4.36 lists the estimated emissions factors for biodiesel (BD100). The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected

performance of biodiesel. The estimates of Arcoumanis (2000) indicate that biodiesel can be expected to meet all future Australian Design Rules for all pollutants except oxides of nitrogen, which may be slightly above Euro3 and Euro4 standards, and possibly the particulate matter standard for Euro3.

Arcoumanis (2000) notes that a blend of 20-30% biodiesel with diesel in heavy vehicles is expected to meet all Euro4 standards (though not all Euro3 standards), as shown in Table 4.37.

Table 4.37
Estimated relative emission factors for 20-30% biodiesel in diesel under different technologies.
Euro2 diesel values (shown in bold) are taken as 1.0.

Technology	CO	CO	HC	HC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.8	**1.0**	0.7	**1.0**	1.0	**1.0**	1.0	1.0	0.8
Euro3	**0.53**	0.5	**0.6**	0.5	**0.71**	0.9	**0.67**	0.7	1.0	0.8
Euro4	**0.38**	0.3	**0.42**	0.3	**0.5**	0.5	**0.2**	0.2	1.0	0.7

5. Canola

5.1 Background

Canola is a member of the *Brassica* Family, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed. Grown for its seed, the seed is crushed for the oil contained within. After the oil is extracted, the by-product is a protein-rich meal used by the intensive livestock industry.

In the 1990s canola production increased dramatically due to new disease resistant varieties (Black Leg Resistance) and strong oilseed prices compared to wheat and wool. Australia has a production land base able to increase canola, though low oilseed prices could restrict expansion.

Canola is a very small seed, which means sowing depth must be controlled to minimise patchy germination. The current sowing practice is to cover the seed lightly with soil, which ensures more protection from drying out after germination.

Canola is generally sown in autumn (late April/early May), develops over winter, flowers in the spring and is harvested early summer (late November/early December) with a growing period of around 180-200 days

Climatic effects such as sudden heat waves can reduce yields and hot dry conditions can limit oil content. Summer weather ensures low moisture (less than 6%) at harvest. Carry-in stocks of canola are minimal because of a lack of on-farm storage.

Canola is a good rotational crop, acting as a break crop for cereal root diseases. However for disease-related reasons, a rotation period of 3-5 years is required for canola crops. Moreover, if on-going research on combating fungal root disease in wheat by seed inoculation proves successful, the land area available for growing canola will come under pressure when canola prices fall.

5.1.1 Canola alternatives

CSIRO has a research program on the use of linola as a substitute for canola (A. Green, CSIRO Plant Industries, pers. comm.) and a joint venture with United Grain Growers of Canada for the development and commercialisation of the crop. Linola is a form of linseed that was developed using conventional plant breeding to make the oil more suitable for edible uses, particularly for cooking oil. Linseed normally has a very high level of linolenic acid, which makes it oxidatively unstable and prevents its use in cooking, particularly commercial cooking (but gives it the drying properties associated with its traditional industrial usage). CSIRO reduced linolenic from 50% down to 3% and consequently raised linoleic up to 65-70%. This makes “linola” oil equivalent in composition and function to high-linoleic sunflower or safflower oils. Green (pers. comm.) would expect linola oil to perform the same as those oils in biodiesel applications.

5.2 Full Fuel-Cycle Analysis

5.2.1 Tailpipe

We are unable to find any tailpipe emissions data for heavy vehicles using pure canola oil. It is over a decade since research was undertaken on the use of pure vegetable oils, such as canola, as heavy-vehicle fuels. Though it is possible to modify diesel engines to run on pure vegetable oils (as discussed in the section on viability and functionality) the consensus of the industry is that biodiesel is a superior fuel. This view was expressed by a number of stakeholders verbally and in writing.

5.2.2 Upstream

Details of canola seed production and processing are given in the chapter that deals with biodiesel.

The upstream emissions for canola oil will be the same as those for canola biodiesel (canola ethyl-ester) except that no transesterification phase is required.

5.2.3 Results

At present pure canola oil is not a viable automotive fuel (see Section 5.3). Thus no results are presented.

5.3 Viability and Functionality

According to material supplied by P. Calais of Murdoch University, though the power output and tailpipe emissions using plant or animal oils are in most cases comparable with the power output and the emissions when running on petroleum diesel fuel, the main problem encountered has been the higher viscosity of the oils causing difficult starting in cold conditions, the gumming up of injectors, the coking-up of valves and exhaust, and the often high melting or solidification point of many vegetable and animal fats and oils. (Pullan et al, 1981)

The viscosity of plant and animal fats and oils varies from hard solids to light oils at room temperature. In most cases, these ‘oils’ are actually a solution of various fatty acids, often with the various components having widely varying melting points. This may give the oil a temperature range over which solidification occurs, with the oil gradually thickening from a thin liquid, through to a thick liquid, then a semi-solid and finally to a solid.

High melting points or solidification ranges can cause problems in fuel systems such as partial or complete blockage as the oil thickens and finally solidifies when the ambient temperature falls (Pullan et al., 1981). Though this also occurs with petroleum-based diesel, particularly as the temperature falls below about ~ 10° C for ‘summer’ formulations and ~ -5° C for ‘winter’ diesels, it is relatively easy to control during the refining process and is generally not a major problem.

Most vegetable oils and some animal oils have ‘drying’ or ‘semi-drying’ properties and it is this which makes many oils such as linseed, tung and fish suitable as the base of paints and other coatings. But it is also this property that further restricts their use as fuels.

Drying results from the double bonds in the oil molecules which can be easily broken by atmospheric oxygen converting the fatty acid into a peroxide. Cross-linking at this site can then occur and the oil irreversibly polymerises into a plastic-like solid (Cole et al., 1977).

In the high temperatures commonly found in internal combustion engines, the process is accelerated and the engine can quickly become gummed-up with the polymerised oil. With some oils, engine failure can occur in as little as 20 hours (Duke, 1983).

The traditional measure of the degree of bonds available for this process is given by the ‘Iodine Value’ (IV) and can be determined by adding iodine to the fat or oil. The amount of iodine in grams absorbed per 100 ml of oil is then the IV. The higher the IV, the more unsaturated (the greater the number of double bonds available) is the oil and the higher the potential to ‘gum up’ when used as a fuel in an engine.

Though some oils have a low IV and are suitable without any further processing other than extraction and filtering, the majority of vegetable and animal oils have an IV which does not permit their use as a neat fuel.

Generally speaking, an IV of less than about 25 is required if the neat oil is to be used in unmodified diesel engines and this severely limited the types of oil that can be used as fuel. Table 1 lists various oils and some of their properties.

The IV can be easily reduced by hydrogenation of the oil (reacting the oil with hydrogen), the hydrogen breaking the double bond and converting the fat or oil into a more saturated oil and reducing the tendency of the oil to polymerise. However this process also tends to increase the melting point of the oil and converts the oil into margarine.

As can be seen from Table 5.1, only coconut oil has an IV low enough to be used without any special precautions in a unmodified diesel engine. However with a melting point of 25°C, the use of coconut oil in cooler areas would obviously lead to problems.

Table 5.1

Melting point and Iodine Values of oils

Oil	**Approx. melting point °C**	**Iodine Value**
Castor oil	-18	85
Coconut oil	25	10
Cotton seed oil	-1	105
Linseed oil	-24	178
Olive oil	-6	81
Palm oil	35	54
Palm kernel oil	24	37
Peanut oil	3	93
Rapeseed oil	-10	98
Soybean oil	-16	130
Sunflower oil	-17	125
Tung oil	-2.5	168
Beef tallow		50
Mutton tallow	42	40
Sardine oil		185

Source: CRC Handbook of Chemistry and Physics, 64th and 76th Ed. pp D-221

All of these problems can be at least partially alleviated by dissolving the oil or hydrogenated oil in petroleum diesel. Linseed oil for example, could be mixed with petroleum diesel at a ratio of up to 1:8 to give an equivalent IV in the mid-twenties. Likewise coconut oil can be thinned with diesel or kerosene to render it less viscous in cooler climates. Obviously the solubility of the oil in petroleum also needs to be taken into account. Another method is to emulsify the oil or fat with ethanol.

Most vegetable oils are a mixture of different esters such as oleic acid (main constituent of olive oil), ricinoleic acid (main constituent of castor oil), linoleic acid and linolenic acid (main constituents of linseed oil), palmitic acid (main constituent of palm kernel oil) and so on. In an analogous way to that in which crude oil is refined to make a useable automotive fuel, canola oil needs to be transesterified to make an automotive fuel that is useable in unmodified diesel engines. When the oil is processed in a transesterfication process, the various fatty acids react with the alcohol to form a mixture of lighter esters and glycerol. The name of the specific fuel is called after the plant (or animal) source plus the alcohol. Made from rapeseed oil and methanol, the biodiesel is called Rape Methyl Ester (RME), from canola oil and ethanol, Canola Ethyl Ester (CEE), and from used McDonald’s cooking oil and ethanol or methanol, McDiesel.

Nevertheless, there is a niche market, mainly in Germany and Austria, in the conversion of diesel vehicles to run on vegetable oil. One example is that of http://www.elsbett.com/gd/tuniinfe.htm in Germany.

5.4 Health Issues

The health issues associated with the use of canola oil in a diesel engine are not known.

5.5 Environmental Impact and Benefits

The environmental issues associated with the use of canola oil in a diesel engine are not known.

6. Hydrated Ethanol

6.1 Background

Development and use of alcohol fuels in transport have for the most part been driven by the desire in many countries to find renewable substitutes for imported petroleum-based fuels. Alcohol fuels have also been used as additives to conventional fuels to improve fuel characteristics. More recently they have been the focus of attention as a possible means of reducing greenhouse gas emissions, and noxious urban emissions from transport.

Ethanol will easily blend with gasoline but blending with diesel requires an emulsifier or additive to form a stable fuel. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations.

Ethanol can be produced in two forms – hydrated and anhydrous. Hydrated ethanol has a purity of 95% suitable for blending with an ignition improver, or as a 15% emulsion in diesel that is known as Diesohol, which is discussed in the next chapter. A second stage refining process is required to produce anhydrous ethanol (100% purity) for use in ethanol blends in petrol, as discussed in Chapter 13. Most industrial ethanol is denatured (to prevent oral consumption) by the addition of small amounts of an unpleasant or poisonous substance.

This chapter will examine hydrated ethanol produced from wheat, sugar cane, molasses and wood, and will discuss one source of ethanol from a non-renewable resource. Hydrated ethanol production is a one-stage refining process, unlike the two-stage anhydrous ethanol. However, from the viewpoint of the LCA, the upstream emissions for ethanol production will be different for every process.

6.1.1 Characteristics of alcohol fuels

Ethanol (C_2H_5OH) is an alcohol, an oxygenated organic carbon compound. It is the intoxicating component of alcoholic beverages, is used as a solvent (methylated spirits), and is widely used in the chemical and pharmaceutical industries. By contrast, diesel is a mixture of a range of hydrocarbon compounds, none of which contains oxygen. In blended fuels, the addition to diesel of the oxygen contained in the alcohol changes a number of important fuel characteristics. These include changes in combustion properties, energy content and vaporisation potential.

The energy content of ethanol ranges from 21 to 23 MJ/L. This compares to 38.6 MJ/L for diesel. The energy content of ethanol depends on whether it is hydrated or anhydrous. Expressed in mass terms the energy content ranges from 24 MJ/kg to 26.7 MJ/kg (http://www.afdc.doe.gov/altfuels.html). Boustead & Hancock (1979) quotes 29.7 MJ/kg. The former values probably represent the lower heating value (LHV) whereas the higher value is probably the higher heating value (HHV).

6.1.2 Production and distribution

Ethanol production

Ethanol can be manufactured numerous sources. For example, a recent thesis examined the life-cycle emissions of ethanol from wine (Ericson and Odehn, 1999). This report examined ethanol from:

- biomass via the fermentation of sugar derived from grain starches or sugar crops;
- biomass via the utilisation of the non-sugar lignocellulosic fractions of crops;
- petroleum and natural gas via an ethylene (C_2H_4) intermediate step (reduction or steam cracking of ethane [C_2H_6] or propane [C_3H_8] fractions).

Ethanol from sugar and starch fractions

At present there are only two commercial sources of ethanol in Australia. It is manufactured from biomass via the fermentation of sugar that is derived either from wheat starch or from molasses. The Australian Greenhouse Office has recently funded a research project to examine the manufacture of ethanol from sugar cane residue (bagasse).

Ethanol from molasses

Ethanol has traditionally been produced in Australia from molasses (C molasses), a low value by-product of the sugarcane industry. CSR Distilleries supplies around half of the Australian ethanol market with an annual plant capacity of 55 million litres (www.csr.com.au/about/Facts_Distilling.htm).

Production of ethanol from molasses constitutes part of the sugar refining process. The overall process consists of the following main steps :

1. **Crushing**: Sugar cane "as farmed" is chopped at the sugar mill to facilitate handling and processing.
2. **Sugar extraction**: This is effected in a countercurrent flow of warm water. The solids after extraction (bagasse) containing less than 0.5% sugar are squeeze-dried to remove maximum of sugar solution (liquor). Dry bagasse is used as fuel to power sugar mill operation.
3. **Raw sugar production**: Sugar-containing liquor is concentrated in evaporators. Crystalline sugar is separated in centrifuges. This process is repeated several times yielding raw sugar. It may be further refined if necessary.
4. **Fermentation of molasses**: Liquid residue from sugar production (molasses) containing approximately 50% sugar and 50% mineral matter is mixed with yeast and fermented yielding 6 to 7% ethanol. Solid residue after fermentation (dunder) contains mostly yeast and minerals and is used as fertiliser. Yeast is sometimes separated and used by the food industry.
5. **Distillation**: The fermented mash, now called "beer," contains about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash is pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Denaturing**: Ethanol that will be used for fuel is denatured at the time of transport with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.

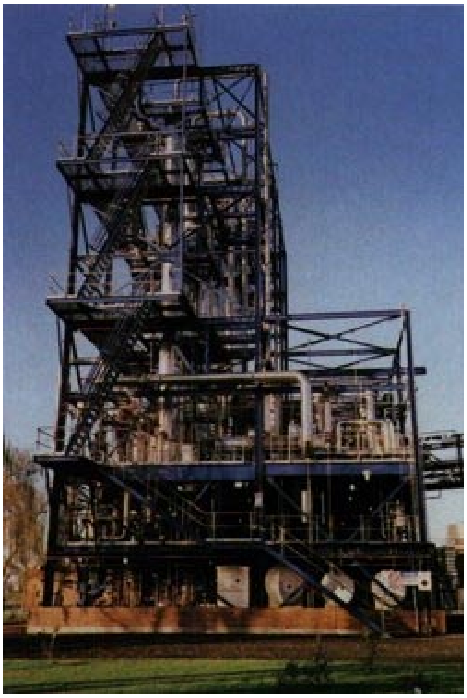

Figure 6.1
The ethanol plant at Manildra's Bomaderry plant near Nowra.
(http://www.manildra.com.au/prospectus/prospectus6.html)

In the case of CSR's azeotropic ethanol-from-molasses plant at Sarina in Queensland, the processing energy input is supplied from combustion of the sugar cane bagasse. Surplus bagasse is also used by CSR for electrical power cogeneration.

Ethanol from wheat starch

Ethanol is also produced from wheat at Manildra's gluten and starch plant at Nowra (Figure 6.1). The major products of the mill are gluten and starch. The ethanol produced from the waste starch stream with further supplementations of starch is essentially a by-product of the gluten manufacturing process.

There are basically seven steps in the ethanol production process from wheat starch:

1. **Milling**: The wheat (or corn, barley, etc.) first passes through hammer mills, which grind it into flour. The flour is then transported by rail to Manildra's industrial plant near Nowra.
2. **Liquefaction**: The meal is then mixed with water and alpha-amylase, and passes through cookers where the starch is liquefied. Heat is applied at this stage to enable liquefaction. Cookers with a high temperature stage (120-150ºC) and a lower temperature holding-period (90ºC) are used. These high temperatures reduce bacteria levels in the mash.
3. **Saccharification**: The mash from the cookers is then cooled and the secondary enzyme (gluco-amylase) added to convert the liquefied starch to fermentable sugars (dextrose), a process called saccharification.
4. **Fermentation**: Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. This carbon dioxide, being completely renewable in origin, is not included in the calculations. Using a continuous process, the fermenting mash flows, or cascades, through several fermenters until the mash is fully fermented and then leaves the final tank. In a batch fermentation process, the mash stays in one fermenter for about 48 hours before the distillation process is started.
5. **Distillation**: The fermented mash, now called "beer", contains about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash is then pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Denaturing**: Ethanol for fuel is then denatured with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.
7. **Co-Products**: The main co-products created in the production of ethanol are carbon dioxide, stockfeed from recovered solids in stillage (distillers grain), and bio-fertiliser from liquid effluent. Carbon dioxide is given off in great quantities during fermentation and many ethanol plants collect that carbon dioxide, clean it of any residual alcohol, compress it and sell it for use to carbonate beverages or in the flash freezing of meat. This carbon dioxide, also being completely renewable in origin, is not included in the calculations. Distillers grains, wet and dried, are high in protein and other nutrients and are a highly valued livestock feed ingredient. Some ethanol plants also create a "syrup" containing some of the solids that can be a separate product sold in addition to the distiller's grain, or combined with it. Manildra uses this process to produce fructose, sugars, glucose syrup, and other products.

APACE Research (R. Reeves, pers. comm.) point out that modern, integrated ethanol-from starch plants, such as that of Manildra, have a processing energy input of approximately 4.5 MJ/L of azeotropic ethanol, and 5.9 MJ/L of anhydrous ethanol. Based on a lower heating value of 19.43 MJ/L for azeotropic ethanol and 21.15 MJ/L for anhydrous ethanol, and assuming natural gas to steam conversion efficiency of 70%, Reeves estimates the processing energy input to be 0.33 of the lower heating value for ethanol for azeotropic ethanol, and 0.40 for anhydrous ethanol. Details are given in Appendix 6.

The starch feedstock used by Manildra for ethanol production is waste starch from Manildra's gluten production, or is derived from reject grain. This means that there is no energy input (or greenhouse gas emissions) associated with this waste product.

Energy and emission data for ethanol production are available from a number of sources including an NREL study (Kadam et al., 1999) and from Swedish data published on the BioAlcohol Fuels Website (Bioalcohol Fuel Foundation, 2000) These data sources look at different processes (from acid to enzyme) and different feedstocks including woodwaste and straw. Data on ethanol has been taken from documents and personal communications with APACE Research (R.Reeves, pers. comm.).

No individual process data is available for the Manildra process so it has been modelled as a black-box with waste product and coal-based heat into the plant, with ethanol as the main output. The ethanol was assumed to be azeotropic so the energy use per litre of ethanol production was 9 MJ.

There are no solid residues available for combustion from Manildra's ethanol-from-starch plant. All liquid effluent streams, principally the underflow from the stripping distillation column, are irrigated onto surrounding land for intensive pasture production. Thus the liquid effluent has displaced use of conventional fertilisers and significantly increased the soil carbon content on Manildra's adjacent environmental farm. Given that the source of carbon is from renewable sources, no credit for fixing fossil carbon is given from a greenhouse perspective. For the same reason carbon dioxide emissions from fermentation are not included as greenhouse impacts as they are from short-term sustainable carbon cycles.

Without clear estimates of the nutrient replacement achieved through land application of effluents, and evidence of this lowering fertiliser use, it is not possible to provide credits for avoided fertiliser use. The effect of these credits is thought to be small in any case.

Because of the low value of the grain feedstocks, they are treated as waste products and not as by-products of the starch process, and thus have no environmental burdens associated with them. If the value of these feedstocks increase, or higher grade grain is used in the Manildra plant, then (as discussed below) an alternative allocation needs to include environmental burdens of the feedstock.

Ethanol from sugar cane residue (bagasse)

The production of ethanol from sugar cane residue is more akin to the production of ethanol from wheat residue than the production of ethanol from molasses. The steps are the same as detailed in the previous section. The main difference is geographic. At present, ethanol produced from sugar cane residue is an activity that takes place in Queensland rather than in the northern New South Wales sugar industry.

Ethanol from wood

Lignocellulose is the structural component of plant biomass and can be derived from trees, grasses, and from cereal and paper wastes. Lignocellulose is also a large component of municipal waste. Both the cellulose and hemicellulose portions of the material (which in the case of plants may comprise 65 to 80 per cent of the non-sugar and starch components) can be converted into ethanol. The proportion of cellulose and hemicellulose from various lignocellulose sources is dependent upon the specific biomass crop. The process is shown in Figure 6.2.

The mass production of ethanol from lignocellulose is still largely in the research and development stage. Production facilities operate mostly at laboratory or pilot scale. The two major research efforts aimed at extracting ethanol from lignocellulose involve technologies using either acid or enzymatic hydrolysis, with the enzymes used being derived from micro-organisms. After hydrolysis the sugars produced are fermented and the ethanol in solution is distilled out, as for ethanol produced from starch and sugar crops.

For the foreseeable future, ethanol produced from non-lignocellulosic biomass sources is likely to be the only feasible option for economical large-scale ethanol production, such that the costs become competitive with that of diesel. Production from sugar and grain crops will dominate ethanol production until the lignocellulose process is proved technically and economically more viable.

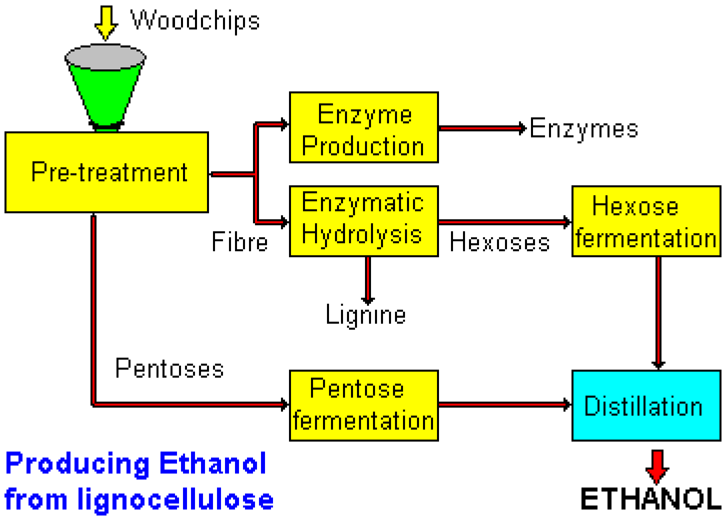

Figure 6.2
Production of ethanol from lignocellulose
Picture is from http://www.swedetrack.com/eflwa22a.htm

Synthetic ethanol from other feedstocks

The most common source of synthetic ethanol is hydration of ethylene. Ethylene itself is a commodity produced on a large scale by oil refineries and broadly used by chemical industries as a feedstock for the manufacture of various chemicals. The majority of ethylene is produced by thermal cracking of hydrocarbons.

The process for hydration of ethylene to ethanol is long established. It involves a two step process using sulfuric acid. In the first step ethylene is reacted with sulfuric acid to form diethyl sulfate:

$$C_2H_4 + H_2SO_4 = C_2H_5OSO_3H$$

$$C_2H_4 + C_2H_5OSO_3H = C_2H_5OSO_2OC_2H_5$$

In the second step diethyl sulfate is hydrolysed with water to ethanol and sulfuric acid:

$$C_2H_5OSO_2OC_2H_5 + 2H_2O = 2C_2H_5OH + H_2SO_4$$

In early 1970's the above process was simplified and direct hydration of ethylene carried out by passing ethylene and water vapour mixture over phosphoric acid supported on a solid surface:

$$C_2H_4 + H_2O = C_2H_5OH$$

This process today accounts for production of the vast majority of synthetic ethanol.

An alternative route to synthetic ethanol involves the Fischer-Tropsch process whereby the syngas (mixture of hydrogen and carbon monoxide) is reacted at pressure over a metal catalyst to yield a mixture of products including alcohols. An appropriate reaction leading to ethanol is as follows:

$$4H_2 + 2CO = H_2O + C_2H_5OH$$

The feedstock for the process (syngas) can be produced from coal via gasification or from natural gas via steam reforming. The problem with the Fischer-Tropsch process for ethanol production is its inherent low selectivity. While catalysts yielding mostly oxygenated products have been developed, it still means that ethanol will be produced along with a number of other alcohols and hydrocarbons. For this reason the Fischer-Tropsch process is used for conversion of natural gas and coal into a range of liquid fuels and waxes rather than specific chemicals.

Other potential routes to synthetic ethanol involve conversion of acetylene to acetaldehyde and subsequent hydrogenation, hydrolysis of esters, or homologation of methanol. None of these is of commercial significance.

6.2 Full Fuel-Cycle Emissions

6.2.1 Tailpipe emissions

The ability of ethanol to contribute to a reduction in greenhouse gas emissions on a FFC basis is very much influenced by the nature of the feedstock and by the source of power used for the production process. CO_2 emissions from the combustion process alone are fairly similar for alcohol fuels and gasoline on an energy equivalent basis, assuming complete combustion.[1]

Table 6.1 reproduces the US value for emissions from diesel and ethanol buses given in Beer et al. (2000). These data are based on 6 data points in the case of 93% ethanol (E93) and 47 data points in the case of 95% ethanol (E95). All of these buses used the same DDC 6V92TA engine. Motta et al. (1996) analysed a subset of these data and note no relationship between the emissions and the vehicle odometer readings.

Table 6.1
Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for diesel and ethanol buses undergoing an urban (CBD) cycle on a dynamometer

Fuel		CO	NMHC	THC	NOx	PM	CO_2	C_2H_5OH	HCHO	CH_3CHO
Diesel	**Average**	**7.72**	**1.30**		**21.26**	**0.79**	**1736.97**			
	Max	28.94	1.75		36.75	1.77	2313.75			
	Min	2.50	0.81		11.50	0.06	1436.88			
E93	**Average**	**9.84**			**5.16**	**0.36**	**2119.17**	**1.27**		
	Max	13.88			6.63	0.46	2256.25	2.86		
	Min	1.56			4.13	0.15	1986.88	0.03		
E95	**Average**	**20.62**	**7.02**	**7.59**	**11.37**	**0.31**	**2154.10**	**4.60**	**0.20**	**1.06**
	Max	38.31	21.04	22.24	20.94	0.61	3611.88	21.17	0.40	2.42
	Min	0.69	0.69	3.51	5.00	0.04	1481.88	0.11	0.01	0.03

C_2H_5OH – ethanol emissions
HCHO – formaldehyde emissions
CH_3CHO – acetaldehyde emissions

On a gram CO_2 emitted per kilometre travelled, the ethanol buses emitted more than the diesel buses, indicating that the fuel economy of the ethanol buses was below theoretical expectations.

The above results refer mainly to older technology buses. As noted below, Ventura bus lines in Melbourne started running an ethanol powered bus on 1 December 2000. The publicity material claims that this is a 100% ethanol-powered bus, but we note that an ignition improver is also being used. CADETT (1998) provides information on these (third generation) ethanol-powered engines and points out that the fuel used is actually 95% ethanol along with an ignition improver (Beraid) and denaturants. The ignition-improving agent Beraid is the non-ionic polymer polyethylene glycol

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[1] Emissions of CO_2 from ethanol are 64.4 grams per MJ, and from diesel 69.7 grams per MJ. Emissions of CO_2 from the combustion of one litre of fuel are 1.5 kilograms for ethanol, and 2.7 kilograms for diesel.

according to Ahlvik and Brandberg (2000). Beraid is necessary in Scania's ethanol engines because the fuel ignites at a much higher temperature than diesel or petrol. The non-ionic polymer works by lowering the ignition temperature of the ethanol to the required level. According to http://www.ethanolmt.org/janfeb01.html#7, the ignition improver used by Ventura is made from animal fat. According to the Swedish KFB web-site, ether can also be used as an ignition improver. The composition of the Swedish fuel is given in Table 6.2.

Table 6.2
Composition of ethanol used in Swedish ethanol buses

Fuel composition		
Ethanol	% by wt	90.2
Ignition improver	% by wt	7.0
MTBE	% by wt	2.3
Isobutanol	% by wt	0.5
Corrosion inhibitor	ppm	90
Colour (red)		

Table 6.3 compares the exhaust emissions from the Swedish ethanol buses with the emissions from diesel buses using the best available technology, namely catalysts, particle traps and ultra-low sulfur diesel.

Table 6.3
Exhaust emissions (g/kWh) from 3rd generation Swedish ethanol buses

Emissions (g/kWh)	Euro2 Standard	Best available diesel	Ethanol Bus Skaraborg
Particles	0.15	0.05	0.04
Oxides of Nitrogen	7.0	6.3	3.93
Carbon Monoxide	4.0	0.1	0.13
Hydrocarbons	1.1	0.1	0.09

6.2.2 Upstream emissions

Full fuel cycle estimates of ethanol (Blinge, 1998; IEA 1999c) indicate that the source of the ethanol is crucial in determining whether ethanol is greenhouse-friendly in relation to diesel.

The Canadian Renewable Fuels Association claims that if corn farmers use state-of-the-art, energy efficient and sustainable farming techniques, and ethanol plants integrate state-of-the-art production processes, the amount of energy contained in the ethanol and its co-products can be more than twice the energy used to grow the corn and convert it into ethanol. See the web site at http://www.greenfuels.org/ethaques.html

Their claim is based on the fact that ethanol contains about 23.6 (high heating value)[2] MJ per litre. The energy content, however, may not be as important as the energy replaced. Due to the higher combustion efficiency of ethanol and its octane credit at the refinery, for example, ethanol can replace 28.1 MJ of gasoline (Levelton Engineering Ltd. and (S&T)[2] Consulting Inc.).

Using the displacement value for calculating the energy content of co-products, there is a further 3.9 MJ/L of energy in ethanol represented by the co-products. The total energy represented by a litre of ethanol is therefore 32 MJ. It takes about 5 MJ of energy to grow the corn required for one litre of

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[2] Also known as Gross Calorific Value

ethanol. This is about 15.5% of the energy in the ethanol and the co-product. It takes a further 14 MJ (43.9% of the energy in the ethanol) to process the corn to ethanol using current technology and practices. It is expected that fully optimised plants will be able to lower this to 11 MJ (35.0%) in the near future.

Because the major consumer of energy in the ethanol chain is the ethanol processing plant, emissions from the use of ethanol could be improved significantly if there were scope for reducing fossil energy consumption on the plant. Taschner (1991) and Colley et al. (1991) have drawn attention to the effect of using co-products of ethanol production (such as cereal straw) as an energy source, rather than leaving it to release greenhouse gases through decomposition. When ethanol is derived from wastes produced during processing sugar and starch crops for other purposes, a significant greenhouse benefit might be realised, if fossil fuel use could be attributed to the primary product (for example gluten or starch).

If ethanol is to provide a major reduction in transport greenhouse gas emissions it will need to be demonstrated that it is both technically and economically feasible on a large scale from lignocellulose processes.

6.2.3 Upstream emissions from C molasses

Sugar cane production assumptions

Ethanol production from the sugar industry is taken to be from the molasses by-product of raw and refined sugar production. Much of the data for sugar cane production has been taken from an unpublished honours thesis by Marguerite Renouf from University of Queensland Environmental Management Centre. Where practical original data sources cited in the thesis have been reproduced.

Sugar cane is produced on the east coast of Australia between Maclean in Northern NSW up to Mossman in North Queensland (Zeitner 2000). Total cane production in 1999/2000 is estimated at around 40.6 million tonnes from a farming area of 419 000 ha giving a yield on 96.8 tonnes per ha (Zeitner 2000). From this harvest 5.6 million tonnes of sugar will be produced, giving a sugar yield from cane of 13.8% (Zeitner 2000). The value of the sugar produced was $257 per tonne. (Zeitner 2000).

Table 6.4
Assumptions for inputs to sugarcane crops

Activity	Power consumption[1] (kWh/ha/yr)	Nitrogen[2] kg N/ha/yr	Phosphorous[3] kg phosphorous (P) /ha/yr	Lime[4] kg lime/ha/yr
Pre-plant field preparation	200.0			
Plant cane	150.0	170	24.2	3.75
Ratoon cane (minimum tillage)	80.0	160	24.2	3.75
Ratoon cane (trash blanketed, zero tillage)	46.7	160	24.2	3.75

Sources:
1 Personal communication with Peter McGuire, BSES extension officer.
2 Moody et al. (1996)
3 Bloesch et al. (1997)
4 Schroeder et al. (2000)

Cane growing

Energy use in land cultivation varies depending on the operation. Sugar cane is initially grown from short section of cane (plant cane). For the next four year the cane is cut and allowed to regrow (ratoon cane) before replanting with new cane stems. Energy and fertiliser inputs to cane farming are listed in

Table 6.4. Relevant outputs from cane growing are in the form of nitrous oxides from soil disturbance and from fertiliser application which are detailed Table 6.5.

Table 6.5
Outputs from cane growing

	applied kg per year	**Emission factor % of N applied**	**Nitrogen emitted kg N/ha/year**	**Conversion factor (N – N$_2$0)**	**N$_2$O per Ha**	**% activity in 5 year rotation**	**Total per annum**
soil disturbance			0.29	1.57	0.46		0.46
plant cane nitrogen	170	1.25%	2.125	1.57	3.34	20%	0.66725
ratoon cane nitrogen	160	1.25%	2	1.57	3.14	80%	2.512
Total N$_2$0 per Ha							3.63

Harvesting of cane

Inputs to cane harvesting are listed in Table 6.6 and consist of energy input to harvesting and loading machinery. Outputs from harvesting are the cane itself, at 96.8 tonnes per ha per year, and combustion emissions from burnt cane harvesting which is assumed to occur in 40% of farms. The National Greenhouse Gas Inventory estimates that the residue left behind after cane harvesting is 25% of the cane weight. The calculation for sugar cane material available for combustion is listed in Table 6.7 with emissions from this combustion being listed in Table 6.8.

Table 6.6
Machinery use for harvesting sugarcane

Activity	**Power consumption (kWh/ha/yr)**
Harvester	30
Loader	104
Total	134

Table 6.7
Data on combustion of sugar cane residues in Australia

Year	**Production**	**Residue to Crop Ratio**	**Fraction of Residue Remaining at Time of Burning**	**Dry Matter Content**	**Burning Efficiency**	**Fraction Burnt**	**Mass of Residue**
1998	39378	0.25	1.0	0.20	0.96	0.40	762.8

Source (NGGIC (2000): APPENDIX TABLE 4—1998 Field Burning of Agricultural Residues 4F-4 (sheet 1)): Crop production of sugar cane)

Table 6.8
Emission factors for field burning of Sugar Cane Trash

		CH$_4$	**N$_2$O**	**NOx**	**CO**	**NMVOC**
Total Mass of fuel burnt	ktonnes	763	763	763	763	763
Total emission	Tonnes	1420	90	5260	55530	3250
Emission factors	kg/tonne	1.86	0.12	6.89	72.78	4.26

Source (NGGIC (2000): APPENDIX TABLE 4—1998 Field Burning of Agricultural Residues 4F-4 (sheet 2): Emissions from on-site agricultural waste burning from sugar cane)

Sugar milling

Sugar milling involves crushing cane with large rollers to extract the sugar juice. This material is then clarified to remove any impurities and concentrated into a syrup by boiling off excess water, seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals have formed and grown. The crystals are separated from the syrup using a centrifuge before more crystals are grown in the syrup.

Molasses (final molasses) is the syrup remaining after the sugar has "passed through the centrifuge for the last time in a mill or refinery." (Sugar Research Institute 2001) The sugar it contains cannot be removed economically and typically includes sucrose (34.1%), reducing sugars (16.5%), ash (11.3%), water (21.8%) and various sugar, gums and acids (16.3%) (Sugar Research Institute 2001). Australian production of molasses in 1999 was 1,119,000 tonnes of which 650,000 tonnes was exported. (Australian Molasses Trading Pty Ltd 2001). This give a molasses yield of around 0.21 tonnes per tonne of sugar produced.

Australian molasses is used mainly in the fermentation (ethyl alcohol, yeast, lysine and monosodium glutamate) and stockfeed industries. (Australian Molasses Trading Pty Ltd 2001). Molasses commercial value is dependent on sugar content, with trading prices in 2000 being around A$100-120 per tonne for 48% sugar content black strap molasses.

The cane material from which the juice was extracted is called bagasse and it has value as a fuel, and has been used to fuel sugar processing for many years. With the advent of greenhouse issues the energy from bagasse is also being harnessed for electricity generation for general grid use.

For bagasse combustion the assumptions shown in Table 6.9 have been made based on work by Dixon et al. (1998).

Table 6.9
Assumptions on bagasse used for energy generation

Parameter	Value
Moisture (wet basis)	50%
Ash (dry basis)	5%
Fibre content	13.8%
HHV (DAF)	19.65 MJ/kg
Gross calorific value (HHV) (as-fired)	9.34 MJ/kg
Net calorific value (LHV)	8.14 MJ/kg
Bagasse yield per tonne of cane	287kg

Source: From Dixon et al. (1998) with net heating value estimated from gross calorific value based on 50% moisture at 2.4 MJ/kg for latent heat of vaporisation for water

Energy use for sugar milling is assumed to be provided by bagasse combustion and is dealt with in more detail in the section on allocation issues for molasses.

Ethanol production.

Inputs to ethanol manufacture have been developed from data provided by NREL (Kadam et al., 1999) and from site specific data provided from personal communications with Energy Strategies Limited on energy use in Sarina and Bomaderry distilleries. The inputs are listed in Table 6.10. The outputs, apart from the azeotropic ethanol, are CO2, which is not accounted as it is from renewable source, and bio-dunder material left after the fermentation process, which can be used as a fertiliser.

Table 6.10
Inputs to fermentation process

Fermentation source for ethanol	Input material	Mass of input material	Energy source	Energy use (primary energy)[2, 3]	Diesel to denature ethanol[1]	Calcined Lime (Aus)[1]	Ammonia[1]	Additional energy to convert to Anhydrous (Brunoro, pers. comm.)
Molasses	Molasses (Aus)	4.32 kg	Bagasse/ coal[3]	13.1 MJ	6 g	2 g	-	0.24 MJ
Wheat	Wheat	2.17 kg	Natural Gas	9 MJ	6 g	2 g	-	0.24 MJ
Wheat from starch waste	Starch	1.12 kg	Coal	9 MJ	6 g	2 g	-	0.24 MJ
Wheat (energy from wheat straw)	Wheat	2.17 kg	Wheat straw	9 MJ	6 g	2 g	-	0.24 MJ
Wood	wood waste	3.68 kg	Wood waste	9 MJ	6 g	2 g	4 g	0.24 MJ

1 Kadam (1999). 2 The value 9 MJ is based on Bomaderry and in agreement with Kadam (1999).
3 For molasses from the Sarina distillery the value is 13.1 MJ. Note that, on an annual basis, 50% of this energy is from bagasse (David Brunoro, Policy Analyst, Energy Strategies Ltd., pers. comm., July 2001).

Allocation issues for molasses

Molasses is an internationally traded commodity, with the key criteria for molasses quality being the total sugar content. In value terms, molasses is worth approximately one seventh the value of sugar on a weight for weight basis, being approximately $50 per tonne for molasses compared with $350 per tonne for refined sugar (Australian Molasses Trading Pty Ltd, 2001).

Following guidance in the international standards on LCA (International Standards Organisation, 1997), allocation of emissions between sugar and molasses is avoided by expanding the system boundary of the study. Under this approach the environmental value, or impact of molasses is not based on prices, but on the environmental impact of replacing the current uses of molasses from which molasses for ethanol production will be taken. This requires detailed knowledge of the market for these material to determine which products would fill any gap left by a shift of molasses into fuels rather than its current uses. Current uses for molasses, according to Australian Molasses Trading Pty Ltd are predominantly exported feedstock and other fermentation processes. As a fermenting agent molasses is likely to be replaced by other fermentable materials and waste products such as wheat starch and low-grade wheat products. Wheat starch is also a minor by-product whose production cannot increase to meet demand and must thus be taken away from other uses. The supply chain of food and crop wastes will eventually be supplemented with dedicated crops for animal feed, and it is the amount and nature of these dedicated crops, (which have the ability to increase production to meet demand rather than shift from one use to another) that represent the impact of increased molasses use in fuels. Figure 6.3 shows the allocation for the range of products produced in the sugar production cycle. Soybeans are used as a proxy for final animal feed product required to fill the gaps in food and agricultural waste products produced by the use of molasses.

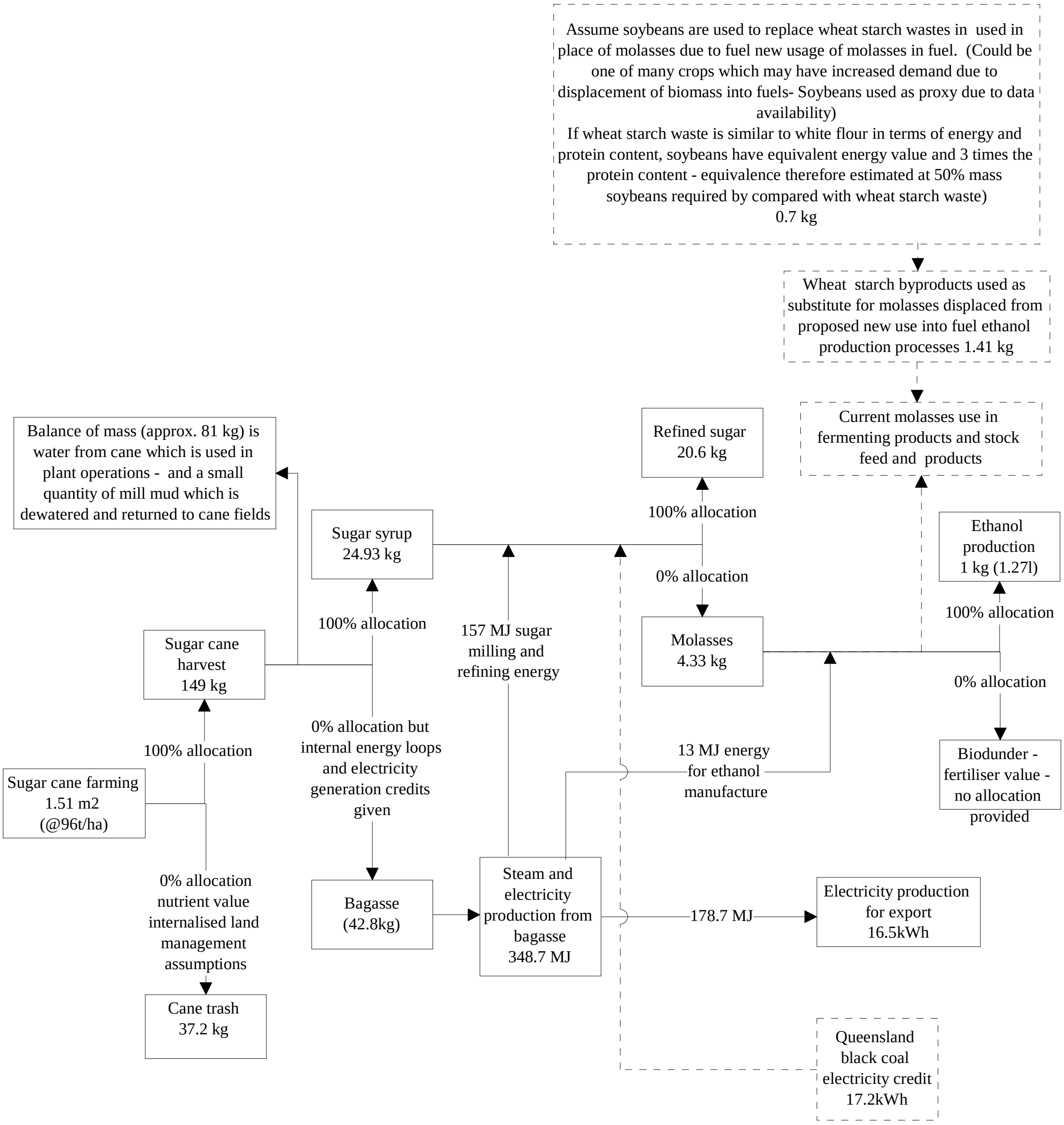

Figure 6.3
Expanded system boundary allocation for molasses use in ethanol for fuels.

An alternate allocation procedure is to use and economic allocation between sugar and molasses in which molasses as a co-product of sugar is allocated an appropriate proportion of the emissions from sugar production. Details of this allocation are shown in Figure 6.3 along with mass flows for different aspects of sugar production.

The other two by-products produced in sugar cane production are sugar cane trash and bagasse. Cane was traditionally burnt prior to harvesting to remove this material. However the trend now is increasingly towards green harvesting, in which the cane trash is removed and left in the field to hold the soil together and provide some nutrients for the next crop. Burnt cane harvesting is used on about 40% of cane lands in Queensland (Queensland Sugar Corporation, 1997), and this has been accounted for in the upstream modelling of sugar production.

Bagasse is the fibrous material remaining after the sugar syrup has been extracted from the sugar cane. This material is generally used for energy production, but can also be used for paper pulp. In this study energy generation is based on data detailed in Table 6.9. Following data from Dixon et al.

(1998) 45% of the energy generation is assumed to be required for sugar mill operations. A further 5.7 MJ is assumed to be used for ethanol production energy requirements. Figure 6.4 shows that this leaves a total of 186 MJ which is available for electricity production for export. After accounting for electricity production losses (assumed at 66%) a total of 17.2 kWh of electricity is exported, with a credit being given for Queensland coal based electricity of the same amount.

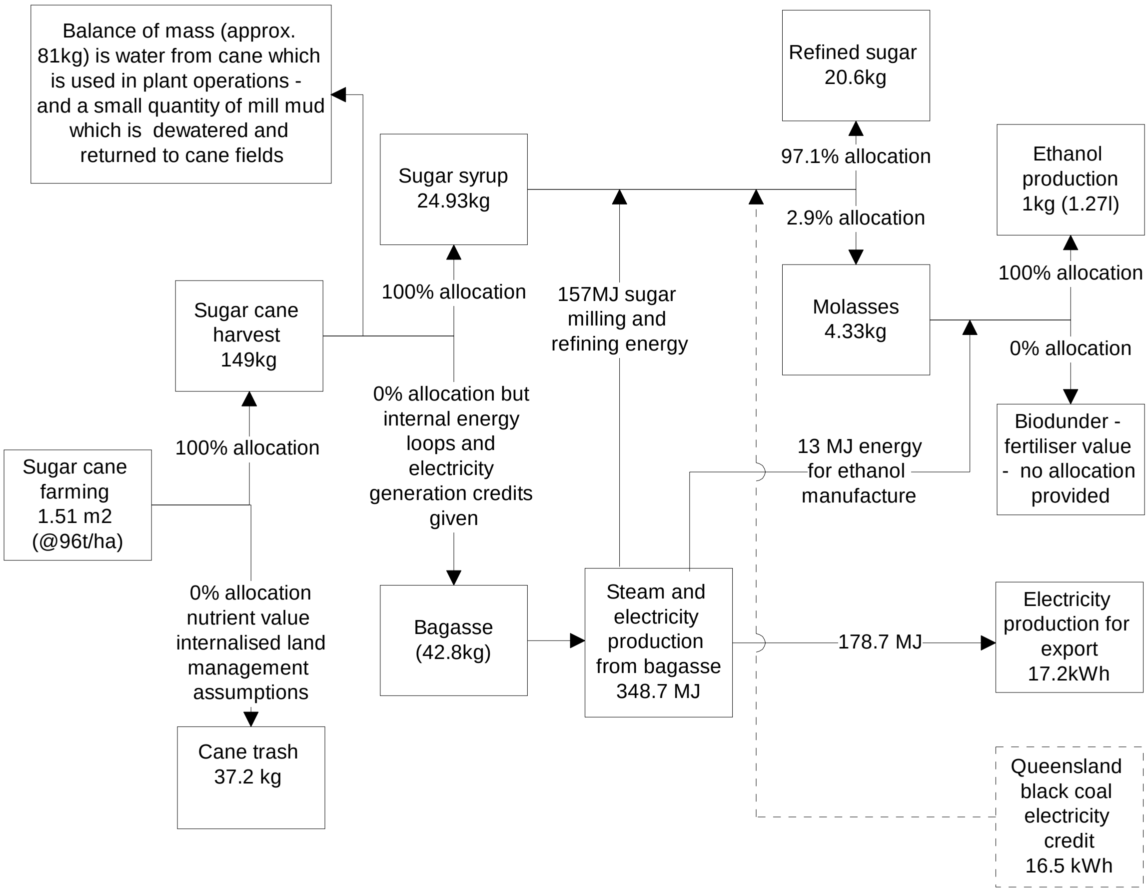

Figure 6.4
Alternative allocation using economic value of co-production for allocation between molasses and sugar.

The results given in the subsequent sections provide quantitative estimates of the exbodied emissions from ethanol under seven scenarios. Two comprise the use of molasses (with expanded system boundaries to determine the energy allocations) and with an economic allocation for the molasses. Three scenarios relate to the use of wheat – one assuming that wheat starch from waste wheat is used, one assuming that premium wheat is used, and one assuming that premium wheat is used for the manufacture of ethanol, with the wheat waste being used to provide power to the plant. There is also a scenario that considers ethanol production from lignocellulose (woodwaste), and a scenario that considers a fossil-fuel based source for ethanol, via ethylene.

6.3 Results

6.3.1 Emissions on a mass per unit energy basis

Table 6.11
Exbodied emissions per MJ for diesel and ethanol

Full Lifecycle	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0858	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0987
NMHC total	g HC	0.140	0.079	0.078	0.071	0.133	0.917	0.591	0.405
NMHC urban	g HC	0.111	0.076	0.076	0.069	0.076	0.860	0.590	0.361
NOx total	g NOx	1.044	0.917	0.916	0.890	1.077	1.027	0.848	0.991
NOx urban	g NOx	0.987	0.888	0.912	0.887	0.919	0.869	0.846	0.966
CO total	g CO	0.253	0.830	0.980	0.298	1.033	3.537	2.087	0.327
CO urban	g CO	0.242	0.824	0.979	0.297	0.301	2.797	2.087	0.316
PM10 total	mg PM10	40.7	26.9	26.4	46.1	49.4	68.2	51.2	29.1
PM10 urban	mg PM10	39.3	26.4	26.3	46.1	46.8	65.6	51.1	28.8
Energy Embodied	MJ LHV	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

Table 6.12
Precombustion emissions per MJ for diesel and ethanol

Precombustion	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0191	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0585
NMHC total	g HC	0.057	0.0122	0.0108	0.0036	0.0658	0.85	0.524	0.338
NMHC urban	g HC	0.027	0.009	0.009	0.002	0.009	0.793	0.523	0.294
NOx total	g NOx	0.100	0.122	0.121	0.095	0.282	0.232	0.053	0.196
NOx urban	g NOx	0.043	0.093	0.117	0.092	0.124	0.074	0.051	0.171
CO total	g CO	0.023	0.543	0.693	0.011	0.746	3.250	1.800	0.040
CO urban	g CO	0.012	0.537	0.692	0.010	0.014	2.510	1.800	0.029
PM10 total	mg PM10	5.42	0.869	0.279	20	23.3	42.1	25.1	3.03
PM10 urban	mg PM10	4	0.294	0.176	20	20.7	39.5	25	2.69
Energy Embodied	MJ LHV	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

Table 6.13
Combustion emissions per MJ for diesel and ethanol

Combustion	Units	LS diesel	Ethanol
Greenhouse	kg CO_2	0.067	0.000 (0.040 for ethylene derived ethanol)
NMHC total	g HC	0.084	0.067
NMHC urban	g HC	0.084	0.067
NOx total	g NOx	0.944	0.795
NOx urban	g NOx	0.944	0.795
CO total	g CO	0.230	0.287
CO urban	g CO	0.230	0.287
PM10 total	mg PM10	35.26	26.08
PM10 urban	mg PM10	35.26	26.08
Energy Embodied	MJ LHV	0	0

Table 6.14
Summary of emissions per MJ for diesel and ethanol

		LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	Pre combustion	0.0191	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0585
Greenhouse	Combustion	0.0667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0402
NMHC total	Pre combustion	0.0565	0.0122	0.0108	0.0036	0.0658	0.8500	0.5240	0.3380
NMHC total	Combustion	0.0835	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670
NMHC urban	Pre combustion	0.0271	0.0086	0.0094	0.0023	0.0089	0.7930	0.5230	0.2940
NMHC urban	Combustion	0.0835	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670
NOx total	Pre combustion	0.1000	0.1220	0.1210	0.0947	0.2820	0.2320	0.0531	0.1960
NOx total	Combustion	0.944	0.795	0.795	0.795	0.795	0.795	0.795	0.795
NOx urban	Pre combustion	0.043	0.093	0.117	0.092	0.124	0.074	0.051	0.171
NOx urban	Combustion	0.944	0.795	0.795	0.795	0.795	0.795	0.795	0.795
CO total	Pre combustion	0.0225	0.5430	0.6930	0.0105	0.7460	3.2500	1.8000	0.0395
CO total	Combustion	0.2301	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874
CO urban	Pre combustion	0.0123	0.5370	0.6920	0.0100	0.0136	2.5100	1.8000	0.0290
CO urban	Combustion	0.2301	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874
PM10 total	Pre combustion	5.42	0.87	0.28	20.00	23.30	42.10	25.10	3.03
PM10 total	Combustion	35.26	26.08	26.08	26.08	26.08	26.08	26.08	26.08
PM10 urban	Pre combustion	4.00	0.29	0.18	20.00	20.70	39.50	25.00	2.69
PM10 urban	Combustion	35.26	26.08	26.08	26.08	26.08	26.08	26.08	26.08
Energy Embodied	Pre combustion	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

6.3.2 Vehicle emissions - trucks (g/km)

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 6.15
Exbodied emissions per km for diesel and ethanol

Full lifecycle	Units (per MJ)	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.9250	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.4693
NMHC total	g HC	1.509	0.866	0.851	0.772	1.453	10.023	6.463	6.673
NMHC urban	g HC	1.192	0.827	0.835	0.757	0.830	9.393	6.453	5.893
NOx total	g NOx	11.250	10.020	10.010	9.730	11.770	11.220	9.270	12.130
NOx urban	g NOx	10.638	9.700	9.960	9.700	10.040	9.495	9.246	11.690
CO total	g CO	2.723	9.071	10.721	3.256	11.301	38.641	22.841	3.835
CO urban	g CO	2.612	9.011	10.701	3.250	3.289	30.641	22.841	3.651
PM10 total	mg PM10	438.4	294.5	288.0	504.0	540.0	745.0	559.0	338.2
PM10 urban	mg PM10	423.1	288.2	286.9	503.0	511.0	716.0	558.0	332.3
Energy Embodied	MJ LHV	12.7	4.41	5.04	4.53	7.09	8.26	28.20	36.20

Table 6.16
Precombustion emissions per km for diesel and ethanol

Precombustion	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.2060	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.0300
NMHC total	g HC	0.609	0.133	0.118	0.0393	0.72	9.29	5.73	5.94
NMHC urban	g HC	0.292	0.094	0.102	0.025	0.098	8.660	5.720	5.160
NOx total	g NOx	1.080	1.330	1.320	1.040	3.080	2.530	0.580	3.440
NOx urban	g NOx	0.468	1.010	1.270	1.010	1.350	0.805	0.556	3.000
CO total	g CO	0.243	5.930	7.580	0.115	8.160	35.500	19.700	0.694
CO urban	g CO	0.132	5.870	7.560	0.109	0.148	27.500	19.700	0.510
PM10 total	mg PM10	58.4	9.5	3.05	219	255	460	274	53.2
PM10 urban	mg PM10	43.1	3.21	1.92	218	226	431	273	47.3
Energy Embodied	MJ LHV	12.7	4.41	5.04	4.53	7.09	8.26	28.2	36.2

Table 6.17
Tailpipe emissions per km for diesel and ethanol

Combustion	Units	LS diesel	Ethanol
Greenhouse	kg CO_2	0.719	0.000 (0.439 for ethylene derived ethanol)
NMHC total	g HC	0.900	0.733
NMHC urban	g HC	0.900	0.733
NOx total	g NOx	10.170	8.691
NOx urban	g NOx	10.170	8.691
CO total	g CO	2.480	3.141
CO urban	g CO	2.480	3.141
PM10 total	mg PM10	380.00	285.00
PM10 urban	mg PM10	380.00	285.00
Energy Embodied	MJ LHV	0	0

Table 6.18
Summary of emissions per km for diesel and ethanol

		LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	Precombustion	0.2060	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.0300
Greenhouse	Combustion	0.7190	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4393
NMHC total	Precombustion	0.6090	0.1330	0.1180	0.0393	0.7200	9.2900	5.7300	5.9400
NMHC total	Combustion	0.9000	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325
NMHC urban	Precombustion	0.2920	0.0941	0.1020	0.0246	0.0977	8.6600	5.7200	5.1600
NMHC urban	Combustion	0.9000	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325
NOx total	Precombustion	1.0800	1.3300	1.3200	1.0400	3.0800	2.5300	0.5800	3.4400
NOx total	Combustion	10.170	8.690	8.690	8.690	8.690	8.690	8.690	8.690
NOx urban	Precombustion	0.468	1.010	1.270	1.010	1.350	0.805	0.556	3.000
NOx urban	Combustion	10.170	8.690	8.690	8.690	8.690	8.690	8.690	8.690
CO total	Precombustion	0.2430	5.9300	7.5800	0.1150	8.1600	35.5000	19.7000	0.6940
CO total	Combustion	2.4800	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409
CO urban	Precombustion	0.1320	5.8700	7.5600	0.1090	0.1480	27.5000	19.7000	0.5100
CO urban	Combustion	2.4800	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409
PM10 total	Precombustion	58.40	9.50	3.05	219.00	255.00	460.00	274.00	53.20
PM10 total	Combustion	380.00	284.99	284.99	284.99	284.99	284.99	284.99	284.99
PM10 urban	Precombustion	43.10	3.21	1.92	218.00	226.00	431.00	273.00	47.30
PM10 urban	Combustion	380.00	284.99	284.99	284.99	284.99	284.99	284.99	284.99
Energy Embodied	Precombustion	12.70	4.41	5.04	4.53	7.09	8.26	28.20	36.20

6.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 6.19.

Table 6.19
Estimated one standard deviation uncertainties (in percent) for hydrated ethanol emissions

	g/MJ	g/t-km	g/p-km
CO_2	15	15	13
NMHC	45	17	73
NOx	21	8	35
CO	40	36	46
PM10	46	45	46

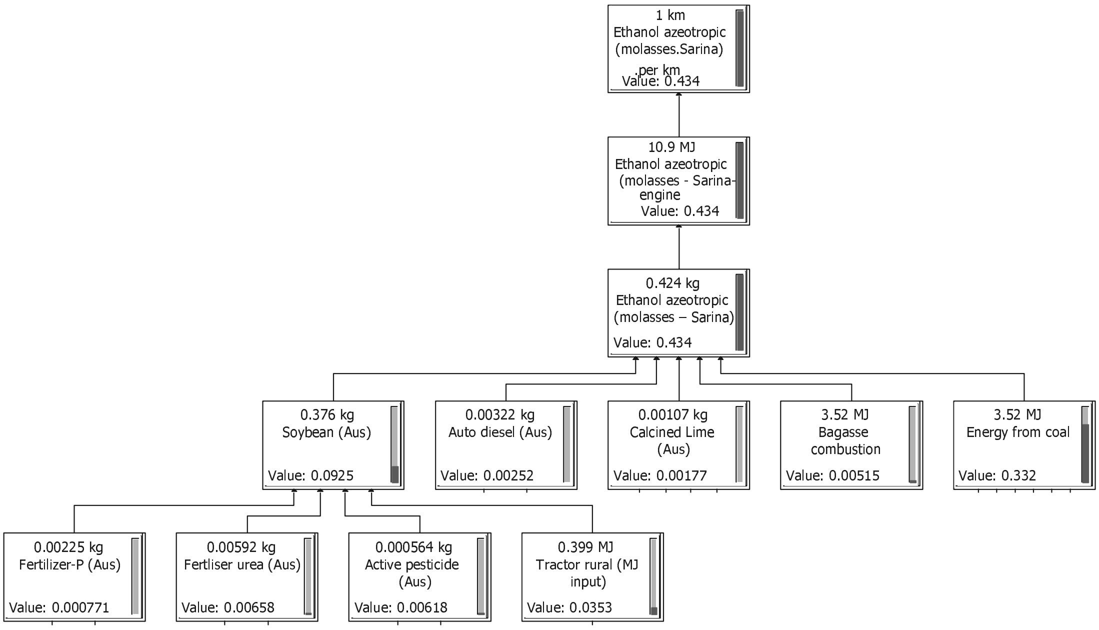

Figure 6.5
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from molasses based on Sarina plant and using expanded system boundary allocation) production and processing and use in vehicle

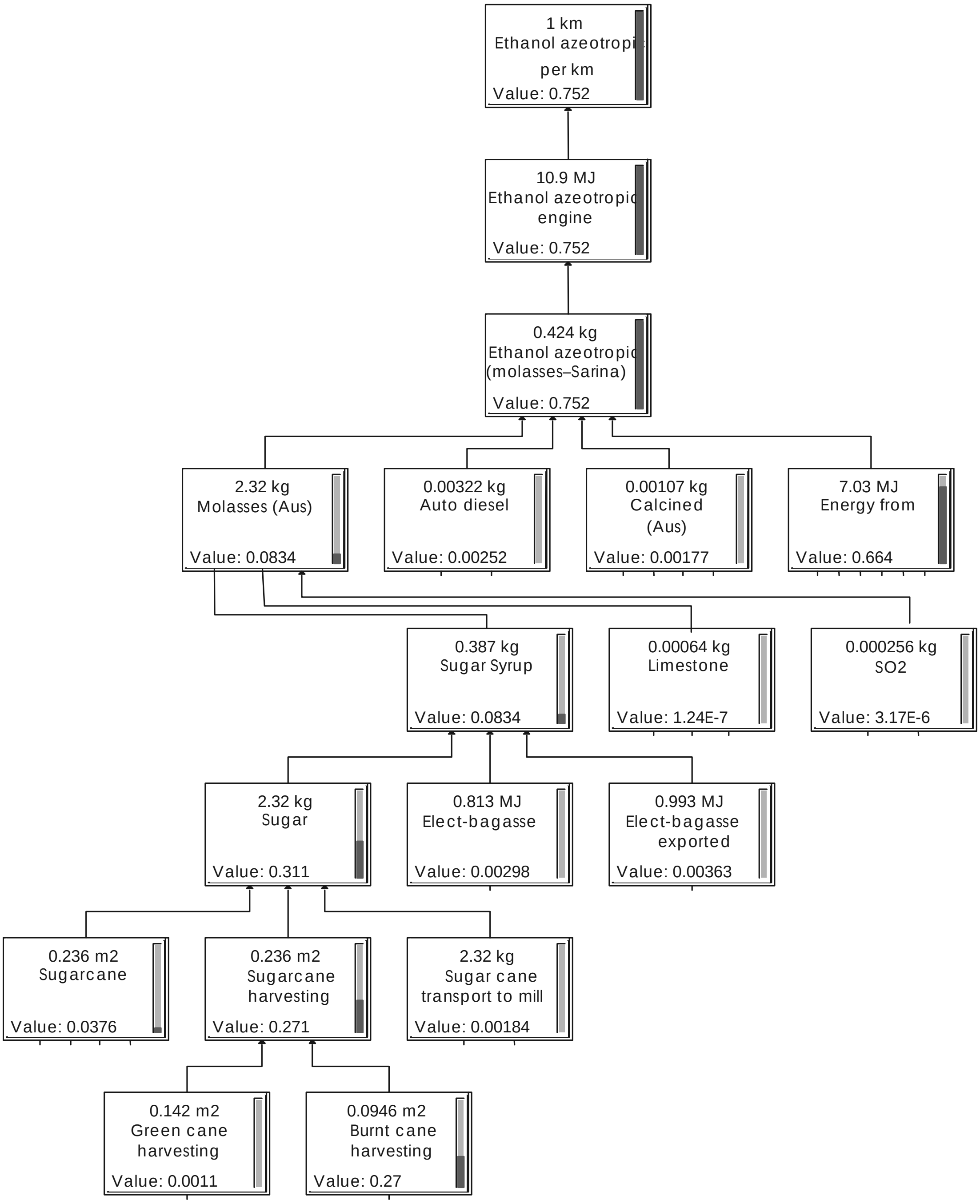

Figure 6.6
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from molasses based on Sarina plant and using economic allocation) production and processing and use in vehicle

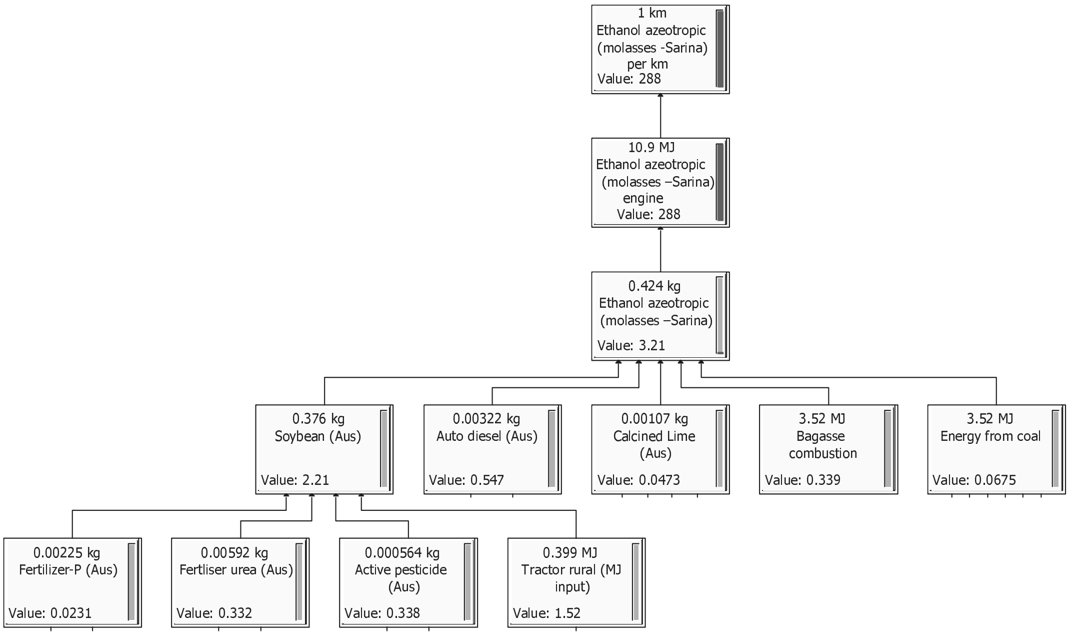

Figure 6.7
Exbodied particulate matter (mg - urban) from ethanol (from molasses based on Sarina plant and using expanded system boundary allocation) production and processing and use in vehicle

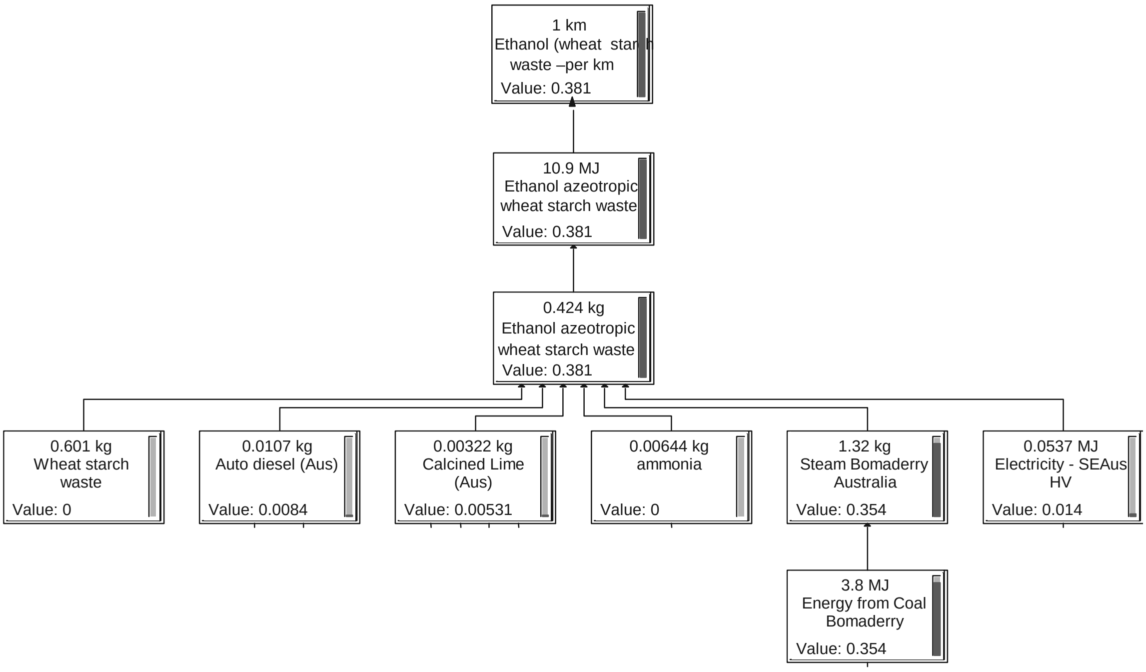

Figure 6.8
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from wheat starch waste based on Manildra plant) production and processing and use in vehicle

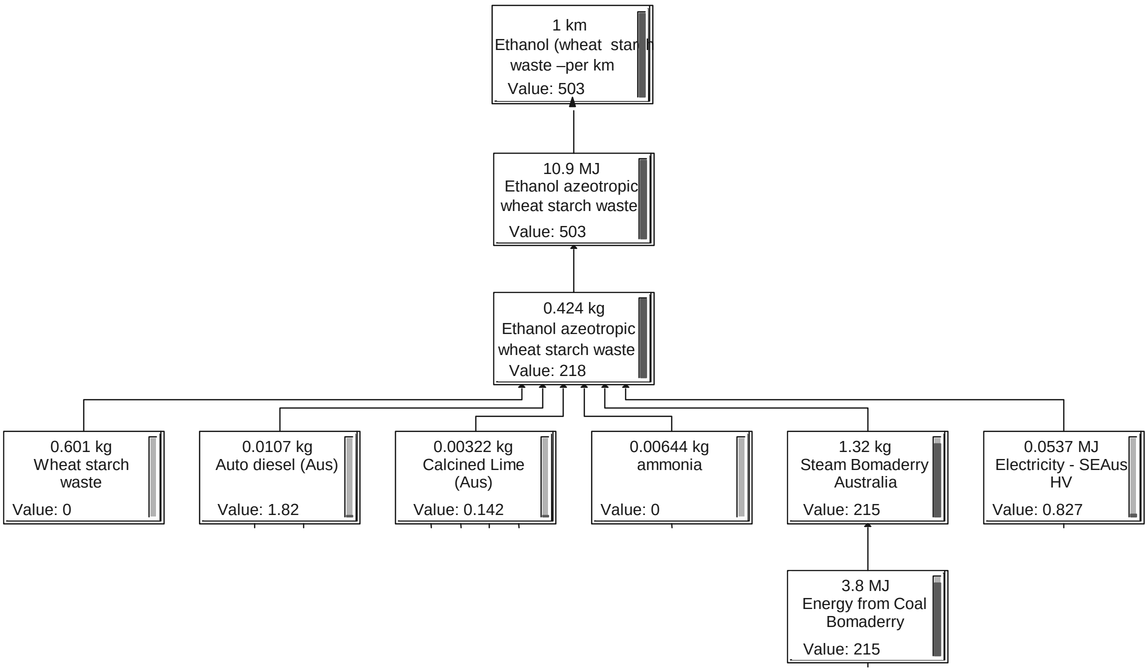

Figure 6.9
Exbodied particulate matter (mg - urban) from ethanol (from wheat starch waste based on Manildra plant) production and processing and use in vehicle

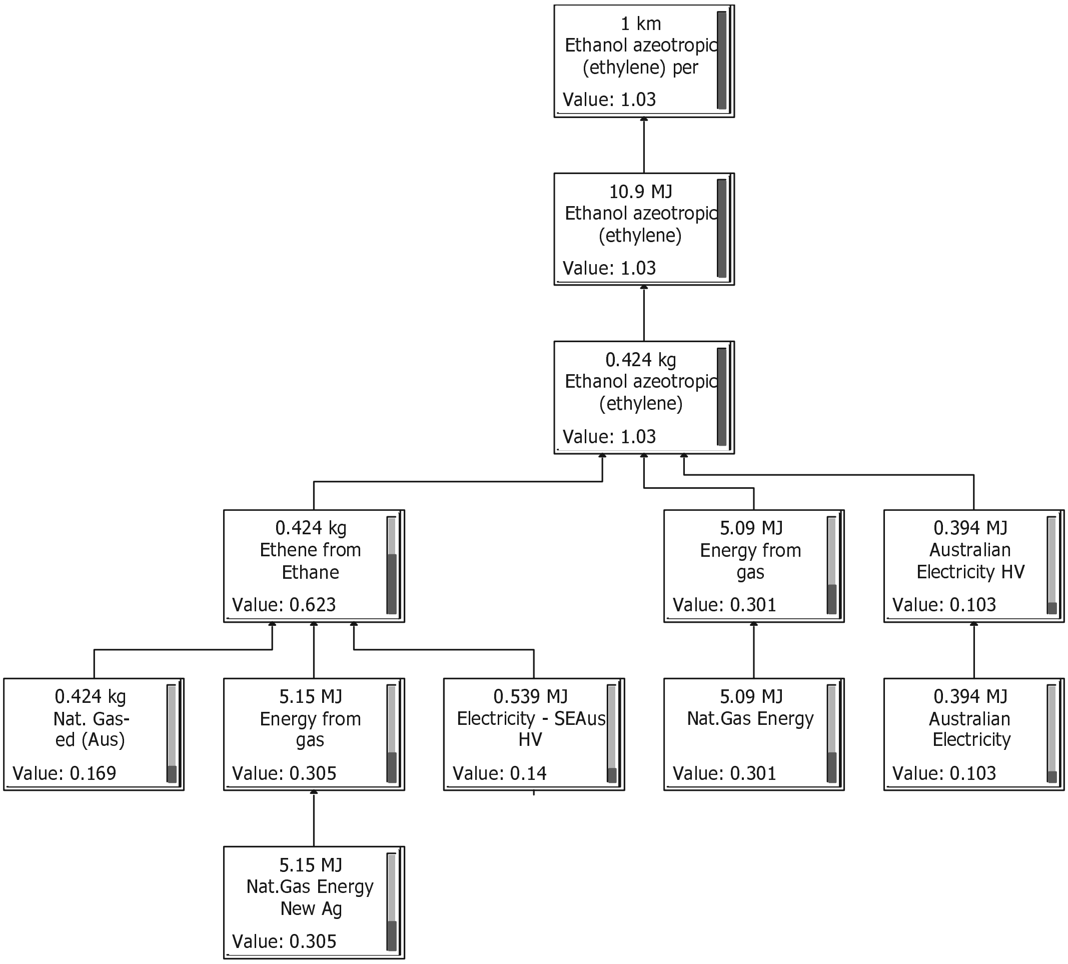

Figure 6.10
Exbodied greenhouse gases in the production of ethanol via ethylene

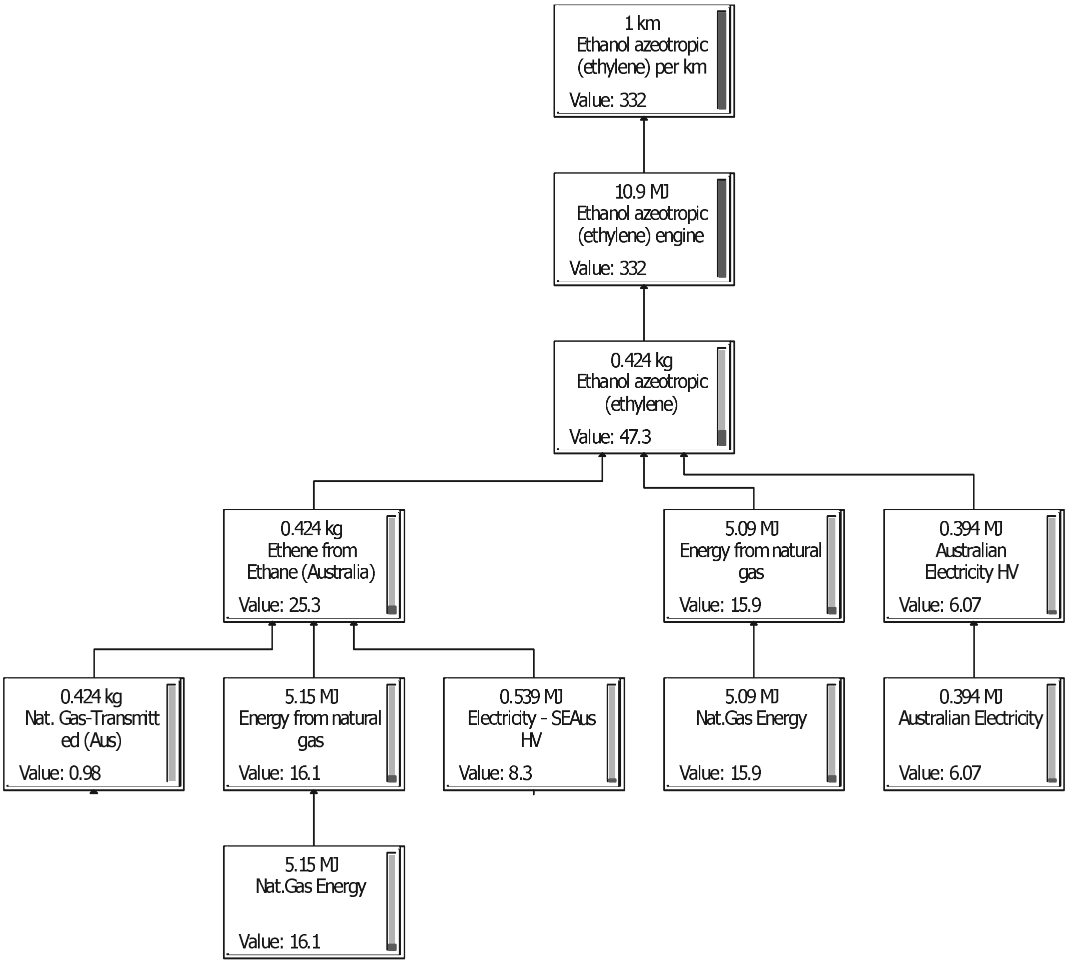

Figure 6.11
Exbodied particulate matter in the production of ethanol via ethylene

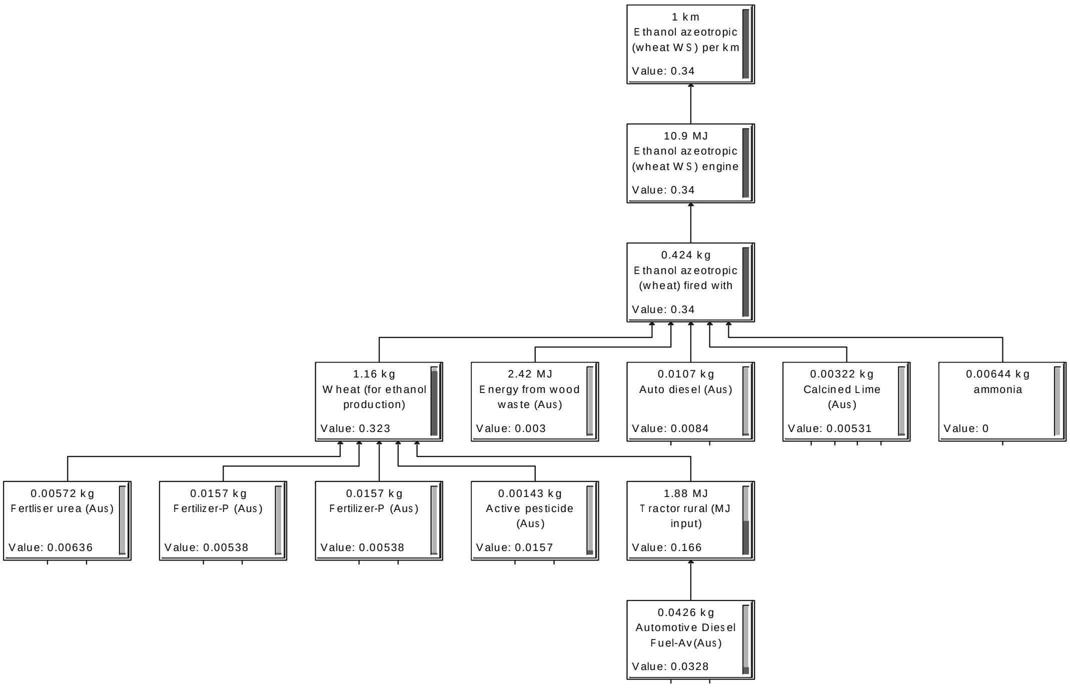

Figure 6.12
Exbodied greenhouse gases in the production of ethanol from wheat using wheat straw for energy

6.4 *Viability and Functionality*

CADDET (1998) notes that third generation ethanol buses have a higher compression ratio (24:1) than the standard diesel engine (18:1) and are equipped with turbo chargers and intercoolers. The third generation fleet also runs with oxidation catalysts. In general, ethanol buses have enlarged holes for the fuel injector, modified injection timing, and increased fuel pump capacity. Gaskets and filters need to be alcohol-resistant. In addition, because ethanol has a tendency to dissolve the oil film on greased metal surfaces, castor oil should be used for fuel pump lubrication. Earlier generations of ethanol buses sometimes emitted an acetic acid smell. The cause was unburned fuel converted into acetic acid in the catalyst and emitted with the exhaust.

On 1 December 2000 Ventura Bus Lines introduced the first two totally renewable fuelled buses into Australia (Figure 6.13). These buses are claimed to operate on 100% ethanol, though as indicated in Table 6.2, it would be more accurate to state that the buses operate on 95% ethanol (by volume) or 90% ethanol (by weight). The ethanol used by Ventura is made from molasses, a by-product of sugar milling by CSR Distilleries. The ethanol is produced at Sarina in the sugar belt of Queensland, shipped to Yarraville for refining, then delivered to the South Oakleigh Depot in the same fashion as diesel. Their web site (www.venturabus.com.au/ven-environmental.html) states:

> **Long Term Supply of Ethanol**
> As ethanol is the base of so many household products, such as Deodorants, Alcoholic Spirits, Methylated Spirits etc, its long term supply is very stable. Therefore there is no issue with future supply of ethanol and costs remain constant as new materials for fermentation are commercialised. Also there is no correlation with the likely substantial escalation of oil prices, as may occur with LPG.
> **Performance of the Ethanol Buses**
> Our customers are aware of the alternative fuel through signage on the buses, promotional literature and our web site editorial. We receive at least one telephone / email or letter each day supporting our recognition of the limited supply of fossil fuel and increasing harmful greenhouse gases. Our Bus Drivers are keen to drive these buses, the responsiveness is better than our newest Euro2 buses and the engine is marginally quieter. The morning bus start-up crews report a huge advantage in starting the ethanol buses compared to the fumes from the modern low emissions Euro2 engines. Given that the engine is so similar to the diesel engine our maintenance staff are happy with the vehicles.
> **The Outlays**
> With a lower energy rating of ethanol than diesel the consumption is much greater than diesel, however after a 20-c/L Commonwealth Government Diesel and Alternative Fuel Grant the operating cost is very similar to the diesel bus. With the assistance of the Commonwealth Vehicle Alternative Fuel Conversion Program the ethanol buses are similar to the current standard Euro3 buses. Ventura has installed a customised fuelling station for the more flammable and corrosive ethanol storage and ethanol pumping, which could cater for another 30 ethanol buses.

There is substantial difference between the Australian experience (based on European technology) and the US experience. The Los Angeles County Municipal Transport Authority (LACMTA, 1999) note that:

> The use of alcohol fuel for transit bus applications was tested by a few transit agencies in the late 1980's and early 1990's with less than desirable results. Methanol and ethanol have a very low cetane number, which makes it difficult to compression ignite. Several approaches have been pursued for converting diesel engines to alcohol operation, including conversion to spark ignition, increasing the cetane number with additives, using a dual-fuel system, and direct injection assisted by glow plugs. Several manufacturers developed experimental and prototype heavy-duty methanol engines, however the Detroit Diesel 6V-92 engine has been the only alcohol fuelled engine certified for transit applications.

Figure 6.13
Ethanol bus currently used by Ventura Bus Lines in Melbourne

> The LACMTA and other transit authorities experienced high rates of engine failure and poor engine reliability with their fleet of methanol buses. LACMTA methanol engines required rebuild at intervals of less than 45,000 miles, while comparable diesel engines needed to be rebuilt at intervals of about 135,000 miles. The LACMTA converted the methanol buses to ethanol in 1995/96 in an effort to improve engine reliability. The ethanol engines failed at rates similar to the methanol buses resulting in the decision to convert the entire fleet to diesel as the alcohol engines failed. As of late December 1998, the original alcohol fleet of 333 buses had been reduced to approximately 45 operational buses.
>
> The poor performance and high operating cost of alcohol buses has also resulted in other transit authorities converting their alcohol buses to diesel fuel. Presently, no domestic transit agency has any methanol or ethanol buses on order, and there are currently no certified methanol/ethanol engines available for heavy-duty bus applications.

6.4.1 Ethanol distribution

Difficulties with the distribution of neat ethanol or ethanol blends arise primarily from the solvency effects of ethanol and from ethanol’s affinity for water. Ethanol is capable of dissolving substances accumulated in pipelines, storage tanks and other components of the distribution system, thus introducing impurities into the fuel. These substances are insoluble in gasoline. Ethanol's affinity for water can result in phase separation of blended alcohol/gasoline fuels, resulting in engine damage or poor vehicle performance. Phase separation is a function of water content, ethanol content, temperature and properties of the fuel. Quality controls for dealing with these issues have been developed over the past 23 years in the United States and Brazil.

Most US distribution is inland, with greater use of ‘dry’ pipelines and systems facilitating the handling of oxygenated fuels. In the USA, ethanol is mostly produced in mid-west farm states, by around 50 commercial scale plants. It is shipped by rail car or truck, rather than by pipeline (the least expensive mode), because of the solvency effect problems identified above. Blending occurs in the tanker truck at the distribution terminal prior to distribution to service stations.

6.5 Health and OHS

6.5.1 Production and transport

The ethanol used in Australia is manufactured from biomass from fermentation of sugar derived from grain or sugar crops. There are research activities to examine biomass via the utilisation of the non-sugar lignocellulosic fraction of crops. Production of these feedstock crops would result in a range of particle and air toxic emissions.

Feedstock transport to the ethanol production facility results in a range of particle and air toxic emissions. Emissions of particulate matter and air toxics could be expected from the ethanol production process. The process includes high temperature cooking and fermentation, which emits acetaldehyde.

Particulate Matter

The LCA estimates for ethanol urban precombustion (truck) PM10 emissions are:

- Wheat: 226 mg/km
- Wheat WS: 431 mg/km
- Wheat starch waste: 235 mg/km
- Molasses (expanded systems boundary): 3 mg/km
- Molasses: 2 mg/km
- Woodwaste: 273 mg/km
- Ethylene: 47 mg/km

The LSD estimate is 43 mg/km. Ethanol urban precombustion (truck) PM10 emissions range from substantially lower to higher than LSD emissions depending on the feedstock.

Air Toxics

The LCA estimates for ethanol urban precombustion (truck) NMHC emissions are:

- Wheat: 0.098 g/km
- Wheat WS: 8.66 g/km
- Wheat starch waste: 0.026 g/km
- Molasses (expanded systems boundary): 0.094 g/km
- Molasses: 0.102 g/km
- Woodwaste: 5.72 g/km
- Ethylene: 5.160 g/km

The LSD estimate is 0.292 g/km thus ethanol urban precombustion (truck) NMHC emissions range from substantially lower to substantially higher than LSD emissions depending on the feedstock.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxics emissions from upstream activities.

6.5.2 Use

Alcohol does not contain sulfur atoms. An increase in the alcohol content of a fuel will thus automatically reduce emissions of sulfur dioxide. (Vehicles running on 100 per cent alcohol could emit a very small amount of sulfurous compounds via combustion of the lubricating oil).

NO_x emissions from ethanol are lower than from diesel, even without a catalytic converter. This is evident in the results of the US ethanol fleet given in Table 6.1 and from the results in Table 6.13 and 6.17.

Boström et al. (1996) examined the health risks from ethanol used as a bus fuel. They found the health risks associated with ethanol to be less than those associated with diesel. Nevertheless, in their study the emissions of butadiene and NO_2 from ethanol buses were such as to exceed guideline values. They note, however, that improved catalyst technology, especially exhaust gas recirculation, will decrease emissions of NO_2 in future generations of vehicles.

Particulate matter

The LCA estimate for ethanol combustion (truck) PM10 emissions of 285 mg/km (for all feedstocks) is less than the LSD estimate of 380 mg/km.

Air Toxics

VOCs play a role in the formation of photochemical smog. Some VOCs produce a detectable odour; others are carcinogenic. Exhaust emissions of VOCs from alcohol vehicles consist mainly of unburnt ethanol. Also, comparisons of exhaust emissions of VOCs from different vehicles, or the same vehicle in different tests, should be interpreted cautiously, as results can be influenced by a wide range of specific fuel and vehicle factors.

Aldehyde (acetaldehyde and formaldehyde) emissions from ethanol are higher than LSD due to the high emissions of acetaldehyde. (Ahlvik and Brandberg, 2000)

Motor vehicle emissions data indicates that the use of ethanol results in substantial reductions in air toxics emissions. Substantial reduction in benzene, 1,3 butadiene, refuelling vapours and particles would occur, while formaldehyde would be emitted at levels similar to gasoline vehicles. However, acetaldehyde emissions would increase substantially. (USEPA, 1993)

The LCA estimate for ethanol combustion (truck) NMHC emissions of 0.733 g/km (for all feedstocks) is similar to the LSD estimate of 0.900 g/km.

6.5.3 Summary

Ethanol upstream emissions of particles and NMHC range from lower to higher than LSD emissions depending on the feedstock. Ethanol tailpipe emissions of particles and NMHC for all feedstocks are marginally less than LSD. Limited tailpipe emissions data indicate that ethanol is likely to reduce benzene and 1,3 butadiene emissions compared with LSD, formaldehyde emissions would be similar, while acetaldehyde emissions would increase substantially.

No comparative emissions data for ethanol and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

6.6 OHS Issues

Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and is a moderate irritant.

Occupation exposure of drivers to diesohol vapours during HDV refuelling was assessed by Workcover in 1992 (NSW Workcover Authority 1999). Normally refuelling is conducted by keeping the fuel dispensing nozzle in the automatic mode with only the last 10-12 litres added manually. The drivers are normally only exposed to diesohol vapours during manual refuelling. The results indicate that levels of diesohol vapours are low and do not represent a significant health hazard to drivers.

The flash point of the emulsion becomes that of alcohol when the alcohol content exceeds 5% of the volume.

Ethanol fuels increases permeation of elastomers that have been used in automotive applications (e.g.: rubber hoses, plastic fuels tanks). Research is required to quantify the permeation impacts of ethanol. (Harold Haskew & Associates. Emission Effects (Permeation) of ethanol in Gasoline. Harold Heskew & Associates Inc. 2001. www.arb.ca.gov)

The OHS issues in the lifecycle of ethanol are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with ethanol compared with LSD, no OHS issues unique to the production and distribution of ethanol have been identified.

6.7 Vapour Pressure Issues

Diesel fuel has very low vapour pressure, but the addition of alcohol to diesel (for example diesohol) creates a fuel with a vapour pressure similar to that of gasoline. While modern gasoline vehicles have some evaporative emission control measures, diesel vehicles do not. Evaporative emissions may be a significant problem from unmodified vehicles using ethanol based fuels, but this needs to be tested.

To contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure, and control evaporative emissions from diesel fuel vehicles.

6.8 Environmental Issues

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid. Provided that the source of ethanol is not fossil fuels then it satisfies ESD principles.

The present use of ethanol is that of a niche fuel. As such, there are no issues related to sustainability. However, if ethanol were to become a dominant fuel then it would have to be based on ligno-cellulose. Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia’s oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia’s croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

Bio-dunder

Bio-dunder (commonly known as dunder) is a by-product of the distilling of ethanol at the CSR Distillery at Sarina. It was once considered a poison, but research into potential uses developed a product that is used by many farmers in the district as a fertiliser and soil conditioner.

Dunder application has been criticised as being the cause of poor water quality in the region. A six-year study concluded that the impacts from application of dunder could not be separated from other agricultural impacts (www.sunfish.org.au/Fishkills/Fishkills.htm). The difficulty in separating the impacts of dunder is perhaps most obvious through observations of creeks and rivers in other regions. Dunder is not used in the Herbert region and yet water quality and habitat impacts are similar.

We also note that Table 6.2 indicates that ethanol when used as a heavy vehicle fuel contains 2.3% MTBE (methyl tertiary butyl ether). This additive has been extensively examined in the US (National Science and Technology Council, 1997) where 15% MTBE (or 7.5% ethanol) was added to petrol to achieve the 2.7% oxygen content required under the Clean Air Act. The use of MTBE is no longer permitted because of concerns in relation to health as a result of groundwater, and hence drinking water, contamination by MTBE.

6.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 6.20 lists the estimated emissions factors for ethanol. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of ethanol. The estimates of Arcoumanis (2000) indicate that ethanol can be expected to meet all future Australian Design Rules for all pollutants except total hydrocarbon, which may be slightly above Euro3 and Euro4 standards.

Table 6.20
Estimated emission factors for ethanol under future technologies

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	1.1	**1.0**	1.1	**1.0**	0.8	**1.0**	0.6	**1.0**	0.9
Euro3	**0.53**	0.5	**0.6**	0.7	**0.71**	0.6	**0.67**	0.4	**1.0**	0.9
Euro4	**0.38**	0.4	**0.42**	0.5	**0.5**	0.4	**0.2**	0.1	**1.0**	0.9

6.10 Summary

6.10.1 Advantages

- As a renewable fuel, ethanol produces significantly less fossil CO_2 than conventional fuels.
- Particle emissions are lower with ethanol than with conventional fuels.
- 1,3 butadiene and benzene levels decrease as the ethanol concentration increases.
- Ethanol contains less sulfur than conventional fuels.

6.10.2 Disadvantages

- The chemical emulsifiers and ignition improvers used to blend ethanol may contain harmful chemicals.
- There are higher emissions of formaldehyde and acetaldehyde from ethanol vehicles than from diesel vehicles.
- There may be an odour problem.

7. Diesohol

7.1 Background

Diesohol is a fuel containing alcohol that comprises a blend of diesel fuel (84.5%), hydrated ethanol (15%) and an Australian developed emulsifier (0.5%). Hydrated ethanol is ethyl alcohol that contains approximately 5% water. The emulsifier is an important component in the preparation of the fuel. It has been developed in Australia by APACE Research.

Development and use of alcohol fuels in transport have, for the most part, been driven by the desire in many countries to find substitutes for imported petroleum based fuels. Alcohol fuels have also been used as additives to conventional fuels to improve fuel characteristics. More recently they have been the focus of attention as a possible means of reducing greenhouse gas emissions and noxious urban emissions from transport.

Anhydrous ethanol will readily blend with petrol. Hydrated ethanol containing more than 2% v/v water is not completely miscible with petrol. Hydrated ethanol is not miscible with diesel but can form an emulsion using a suitable emulsifier. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations. Work in Australia by APACE Research Ltd has produced an ethanol and diesel emulsion called ‘diesohol’. APACE claims that a diesohol emulsion containing up to 30 per cent ethanol will run in a diesel engine, with the engine requiring little or no modification. The ACTION bus fleet in Canberra trialed three new buses running on diesohol (Scott et al., 1995; Joseph, 1996). Sydney Buses also used such buses from 1993 to 1998 (Figure 7.1).

Figure 7.1
Diesohol bus used by Sydney Buses from 1993 to 1998.

7.2 Characteristics of Diesohol

Table 7.1 lists some of the physical properties of diesohol prepared from regular diesel and from low sulfur diesel.

Table 7.1
Diesohol fuel quality specifications (APACE Research Ltd, 1999)

Fuel parameter	Regular Diesohol	Low Sulfur Diesohol
Sulfur (ppm)	1000	300
Density at 15^{o}C (kg/m^3)	846.5	846.5
Distillation T95 (^{o}C)	336.4	330.7
Calculated cetane index	52	52
Ash & suspended solids (ppm)	100	100
Viscosity (mm^2/s)	3.568	3.256
Water content (mg/L)	8860	10551
Hydrogen content (mass %)	13.7	12.8
Carbon content (mass %)	86.2	87.2

The lower calorific value of ethanol is 20.6 MJ/L (25.6MJ/kg), which drops to 19.41 MJ/L (23.96 MJ/kg) when hydrated 5% v/v with water. Thus the lower calorific value of a blend of 15% hydrated ethanol with diesel (which has a lower calorific value of 35.70 MJ/L or 42.75 MJ/kg) is 33.26 MJ/L. According to APACE Research Ltd. the thermodynamic cycle is affected by the extended ignition delay due to the alcohol. This tends to increase the thermal efficiency, especially under full load conditions. The power reduction is thus less than calculated from calorific values alone. For example, use of 15% v/v ethanol emulsion is calculated to result in a 7.3% reduction in power. However, a reduction of only 3-4 % is usually obtained in practice.

7.3 Production and Distribution

Because ethanol comprises only 15% of diesohol, this section briefly reviews the upstream processes associated with ethanol production. Greater detail is given in the previous examination of ethanol as a fuel in its own right.

7.3.1 Ethanol production

At present there are only two sources of ethanol in Australia. It is manufactured from biomass via the fermentation of sugar that is derived either from wheat starch or from molasses. Starch and sugar crops in Australia that have received attention as a potential source of ethanol include cassava in Queensland; sugarcane in Queensland and northern NSW; sweet sorghum in Queensland, NSW and Victoria; Jerusalem artichokes and potatoes in Victoria; sugar beet in Victoria and Tasmania; and cereals in NSW and Victoria. In Sweden, much of the ethanol used as a fuel comes from excess European wine production (Ericson and Odehn, 1999).

7.3.2 Ethanol from sugar

Ethanol has traditionally been produced in Australia from molasses, a by-product of the sugarcane industry. CSR supplies around half of the Australian ethanol market with an annual plant capacity of 55 million litres (www.csr.com.au/about/Facts_Distilling.htm).

Production of ethanol from molasses constitutes part of the sugar refining process. The overall process consists of the following main steps:

1. **Crushing** : Sugar cane "as farmed" is chopped at the sugar mill to facilitate handling and processing.
2. **Sugar extraction** : This is effected in a countercurrent flow of warm water. The solids after extraction (bagasse) containing less than 0.5% sugar are squeeze-dried to remove maximum of sugar solution (liquor). Dry bagasse is used as fuel to power sugar mill operation.
3. **Raw sugar production** : Sugar-containing liquor is concentrated in evaporators. Crystalline sugar is separated in centrifuges. This process is repeated several times yielding raw sugar. It may be further refined if necessary.
4. **Fermentation of molasses** : Liquid residue from sugar production (molasses) containing approximately 50% sugar and 50% mineral matter is mixed with yeast and fermented yielding 6 to 7% ethanol. Solid residue after fermentation (dunder) contains mostly yeast and minerals and is used as fertiliser. Yeast is sometimes separated and used by the food industry.
5. **Distillation**: The fermented mash, now called "beer," contains about 10% alcohol, as well as all the non-fermentable solids from the sugar and the yeast cells. The mash is pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Dehydration**: The alcohol from the top of the column then passes through a dehydration system where the remaining water is removed. Most ethanol plants use a molecular sieve to capture the last drop of water in the ethanol. The alcohol product at this stage is called anhydrous (pure, without water) ethanol and is approximately 200 proof.
7. **Denaturing**: Ethanol that will be used for fuel is then denatured with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.

APACE Research (R. Reeves, pers, comm.) notes that molasses is the residue from the production of crystal sugar for food. As residue it has a lower (though non-zero) economic value than the primary output. In the case of CSR's azeotropic ethanol-from-molasses plant at Sarina in Queensland, the processing energy input is supplied from combustion of the sugar cane bagasse. Surplus bagasse is also used by CSR for electrical power cogeneration.

7.3.3 Ethanol from starch

Ethanol is also produced from wheat at Manildra's gluten and starch plant at Nowra, Figure 7.2. The major products of the mill are gluten and starch. The ethanol produced from the waste starch stream with further supplementations of starch is essentially a by-product of the gluten manufacturing process.

Figure 7.2
The ethanol plant at Manildra's Nowra plant.
(http://www.manildra.com.au/prospectus/prospectus6.html)

There are basically eight steps in the ethanol production process from wheat starch:

1. **Milling**: The wheat (or corn, barley, etc.) first passes through hammer mills, which grind it into a fine powder called meal.
2. **Liquefaction**: The meal is then mixed with water and alpha-amylase, and passes through cookers where the starch is liquefied. Heat is applied at this stage to enable liquefaction. Cookers with a high temperature stage (120-150ºC) and a lower temperature holding-period (90ºC) are used. These high temperatures reduce bacteria levels in the mash.
3. **Saccharification**: The mash from the cookers is then cooled and the secondary enzyme (gluco-amylase) added to convert the liquefied starch to fermentable sugars (dextrose), a process called saccharification.
4. **Fermentation**: Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. This carbon dioxide, being completely renewable in origin, is not included in the calculations. Using a continuous process, the fermenting mash flows, or cascades, through several fermenters until the mash is fully fermented and then leaves the final tank. In a batch fermentation process, the mash stays in one fermenter for about 48 hours before the distillation process is started.
5. **Distillation**: The fermented mash, now called "beer," contains about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash is then pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Dehydration**: The alcohol from the top of the column then passes through a dehydration system where the remaining water is removed. Most ethanol plants use a molecular sieve to capture the last drop of water in the ethanol. The alcohol product at this stage is called anhydrous (pure, without water) ethanol and is approximately 200 proof.
7. **Denaturing**: Ethanol for fuel is then denatured with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.
8. **Co-Products**: There are two main co-products created in the production of ethanol: carbon dioxide and distillers grain. Carbon dioxide is given off in great quantities during

> fermentation and many ethanol plants collect that carbon dioxide, clean it of any residual alcohol, compress it and sell it for use to carbonate beverages or in the flash freezing of meat. This carbon dioxide, also being completely renewable in origin, is not included in the calculations. Distillers grains, wet and dried, are high in protein and other nutrients and are a highly valued livestock feed ingredient. Some ethanol plants also create a "syrup" containing some of the solids that can be a separate production sold in addition to the distiller's grain, or combined with it. Manildra uses this process to produce fructose.

Energy and emission data for ethanol production are available from a number of sources including a NREL study (Kadam et al., 1999) and from Swedish data published on the BioAlcohol Fuels Website (Bioalcohol Fuel Foundation, 2000). These data sources look at different processes (from acid to enzyme) and different feedstocks including woodwaste and straw. However, given the nature of diesohol as a proprietary fuel blend being produced at a specific plant from specific feedstocks, data on ethanol for diesohol production has been taken from documents and personal communications with APACE Research (R. Reeves, pers. comm.). They point out that modern, integrated ethanol-from starch plants, such as that of Manildra, have a processing energy input of approximately 4.5 MJ/L of azeotropic ethanol, and 5.9 MJ/L of anhydrous ethanol. Based on a lower calorific value of 19.43 MJ/L for azeotropic ethanol and 21.15 MJ/L for anhydrous ethanol, and assuming natural gas to steam conversion efficiency of 70%, Reeves estimates the processing energy input to be 0.33 of the lower calorific value for ethanol for azeotropic ethanol, and 0.40 for anhydrous ethanol (as described in Appendix 6).

No individual process data is available for the Manildra process so it has been modelled as a black box with waste product and coal based heat into the plant, with ethanol as the main output. The ethanol was assumed to be azeotropic so the energy use of ethanol production was 9 MJ/L (as in Table 6.10 in the chapter on hydrated ethanol).

There are no solid residues available for combustion from Manildra's ethanol-from-starch plant. All liquid effluent streams, principally the underflow from the stripping distillation column, are irrigated onto surrounding land for intensive pasture production. Thus the liquid effluent has displaced use of conventional fertilisers and significantly increased the soil carbon content. Given that the source of carbon is from renewable sources, no credit for fixing fossil carbon is given from a greenhouse perspective. For the same reason carbon dioxide emissions from fermentation are not included as greenhouse impacts as they are from short-term carbon cycles.

Without clear estimates of the nutrient replacement achieved through land application of effluents, and evidence of this lowering fertiliser use, it is not possible to provided credits for avoided fertiliser use. The effect of these credits is thought to be small in any case.

It is assumed that the starch feedstock used by Manildra for ethanol production is waste starch from Manildra's gluten production, or is derived from reject grain. Because of the low value of these feedstocks, they are treated as waste products and not as by-products of the starch process, and thus have no environmental burdens associated with them. If the value of these feedstocks increase, or higher grade grain is used in the Manildra plant, then an alternative allocation will be needed to include environmental burdens of the feedstock. Modelling of ethanol, as for fuels other than diesohol, included in the next stage of the report, will include allocation procedures for production from dedicated feedstocks and valuable by-products.

Emulsifier for diesohol

According to APACE research the emulsifier that allows the ethanol and the diesel to blend consists of a styrene-butadiene copolymer which is dissolved in the diesel fuel, and a polyethyleneoxide-polystyrene (PEOPS) copolymer which is dissolved in the hydrated alcohol. No values are known as to the proportions of these substances so a total emulsifier is assumed to consist of 50% of each co-polymer. The co-polymers are then also assumed to consist of 50% of the two polymer constituents. The resultant mixture for the emulsifier is show in Table 7.2

Table 7.2
Data summary for 1kg of emulsifier used in diesohol

Component	Amount Assumed	Inventory data source
Sytrene	250 g	Steinhage (1990) modified with Australian feedstocks
Butadiene	250 g	Steinhage (1990) & Reinders (1983) modified with Australian feedstocks
Polyethylene Oxide	250 g	Grant (1999) as polyethylene
Polystyrene	250 g	Same as for Styrene with polymerisation data from Steinhage (1990)

7.4 Diesohol Emissions

7.4.1 Upstream

Hydrated (or azeotropic) ethanol derived from sugar, or ethanol derived from wheat starch, may be used for production of diesohol. Hydrated ethanol production is a one-stage refining process, unlike the two-stage anhydrous ethanol. However, from the viewpoint of the LCA, the upstream emissions for ethanol production will be different for both processes.

There are two reasons for this. First, there are differences in energy demand for both processes. Second, as in both cases ethanol is a co-produced with other value added products, there will be differences in emissions allocation as per ISO 14040.

In the past, the ethanol used for diesohol came from the Manildra refinery. The calculations in this report are based on the present source of ethanol for diesohol, namely the CSR refinery at Sarina.

7.4.2 Tailpipe

APACE Research (Ernie Lom, pers. comm.) provided results from Swedish tests of diesohol conducted in 1997[1]. These results (Table 7.3) are for fuels that blend diesohol with Swedish Diesel fuel and with European diesel (EDsl) meeting EN590 specifications. European diesel is a low-sulfur fuel. Swedish diesel is an ultra-low sulfur fuel.

Table 7.3
Results of Swedish tests of diesohol (g/MJ) with low sulfur (ED) and ultra-low sulfur (SwD) fuels

Fuel	CO_2	CO	NOx	HC	PM	Fuel Use
SwD	205.6	0.4	1.9	0.2	0.047	98.81
SwD+OXC	211.1	0.4	1.9	0.2	0.033	101.97
SwDhol	200.0	0.5	2.0	0.2	0.030	99.72
SwDhol+OXC	200.0	0.4	2.0	0.2	0.017	98.39
EDsl	205.6	0.4	1.9	0.2	0.061	97.42
EDhol	205.6	0.5	2.0	0.2	0.039	100.11

OXC = Oxidation catalyst

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[1] Westerholm, R., Christensen, A., Tornqvist, M., Ehrenberg, L. & Haupt, D. (1997) Chemical and biological characterisation of exhaust emissions from ethanol and ethanol blended diesel fuels in comparison with neat diesel fuels, KFB Report 1997:17, Kommunikations Forsknings Beredningen (Swedish Transport and Communications Research Board) Stockholm.

The ACTION bus fleet in Canberra trialed three new buses running on diesohol (Scott et al., 1995; Joseph, 1996). Sydney buses also used such buses, until 1998, from their Burwood depot (Figure 7.1) and the results of emission testing of these buses is given in APACE Research Ltd (1999).

The tests on diesohol that were conducted by the NSW EPA (Scott et al., 1995) compared the performance of three ACTION ethanol-fuelled buses with three buses fuelled by diesel. The results are given in g/kWh. They have been converted to g/MJ and to g/km on the basis of the observed fuel consumption, which ranged from 217 to 341 g/kWh, and on the fuel economy, which ranged from 36.79 L/100 km to 46.96 L/100 km. The density for all fuels was assumed to be 840 g/L. The results are summarised in Table 7.4, Table 7.5 and Table 7.6. We have analysed the results presented on both the Canberra and Sydney buses

Table 7.4
Results of testing of Canberra buses (Scott et al., 1995; Joseph, 1996)

Fuel	CO_2	CO	NOx	HC	Fuel Use
Diesohol (g/MJ)	296	0.47	4.25	0.25	101
Diesel (g/MJ)	296	0.39	4.81	0.25	95
Diesohol (g/km)	981	1.57	14.09	0.83	
Diesel (g/km)	963	1.27	15.66	0.81	

Table 7.5
Results of testing of Sydney buses (APACE Research Pty Ltd, 1999)

Fuel	CO_2	CO	NO_x	HC	PM	Fuel Use
Diesel (g/MJ)	212	0.22	1.98	0.14	0.05	60.8
E15 (g/MJ)	212	0.25	1.88	0.15	0.04	65.6
E17 (g/MJ)	210	0.22	1.97	0.14	0.04	65.0
E20 (g/MJ)	213	0.25	1.87	0.15	0.03	66.4
LSD (g/MJ)	207	0.22	2.08	0.17	0.04	60.3
LSDiesohol(E15) (g/MJ)	206	0.26	1.97	0.16	0.03	65.6
Diesel (g/km)	1310	1.37	12.20	0.89	0.28	
E15 (g/km)	1274	1.49	11.33	0.89	0.24	
E17 (g/km)	1274	1.31	11.95	0.84	0.21	
E20 (g/km)	1263	1.49	11.09	0.91	0.20	
LSD (g/km)	1291	1.39	12.97	1.04	0.25	
LSDiesohol(E15) (g/km)	1242	1.57	11.85	0.99	0.19	

Table 7.6
Results of testing of Sydney buses for air toxics (APACE Research Pty Ltd.)

Fuel	Formaldehyde	Acetaldehyde.
Diesel (g/MJ)	0.0014	0.0033
E15 (g/MJ)	0.0011	0.0061
E17 (g/MJ)	0.0017	0.0061
E20 (g/MJ)	0.0014	0.0067
LSD (g/MJ)	0.0022	0.0061
LSDiesohol(E15) (g/MJ)	0.0019	0.0058
Diesel (g/km)	0.0086	0.0206
E15 (g/km)	0.0064	0.0350
E17 (g/km)	0.0096	0.0353
E20 (g/km)	0.0079	0.0377
LSD (g/km)	0.0139	0.0381
LSDiesohol(E15) (g/km)	0.0111	0.0334

In addition, Scott et al. (1995: Table 25) present a summary of the aldehyde emissions from Canberra buses using diesohol, in concentration units. At a speed of 50 km/h under 25% load, the formaldehyde emissions are as given in Table 7.7.

Table 7.7
Concentrations of aldehydes emitted from Canberra buses at 50 km/hr under 25% load.

Fuel	Formaldehyde	Acetaldehyde	Acrolein	Total Aldehydes
Diesohol (ppmv)	0.658	1.667	0.483	2.792
Diesel (ppmv)	0.783	1.342	0.85	2.958

7.5 Full Fuel-Cycle Analysis of Emissions

APACE Research (R. Reeves, personal communication) provided estimates of the life-cycle carbon dioxide emissions of diesohol using the energy balance method of Lynd (1996). These calculations are reproduced in Appendix 6. They claim the following emissions:

- 80 gCO_2/MJ for diesel fuel
- 28 gCO_2/MJ for Manildra azeotropic ethanol
- 31 gCO_2/MJ for Manildra anhydrous ethanol
- 4 gCO_2/MJ for CSR azeotropic ethanol from molasses
- 16 gCO_2/MJ for ethanol from dedicated lignocellulosic crops
- 6 gCO_2/MJ for ethanol from lignocellulosic residue material.

These values may be compared with those calculated by Beer et al. (2000) who estimated life-cycle CO_2 emissions to be 80 gCO_2/MJ for diesel fuel and 36 gCO_2/MJ for ethanol from lignocellulose. We believe that discrepancy between this latter value, obtained using a bottom-up approach and the 16gCO_2/MJ estimated by APACE, using a top-down approach are indicative of the range of uncertainty associated with estimates of full fuel cycle greenhouse gas emissions.

Despite the energy savings associated with lignocellulosic ethanol, there is no commercial production of such ethanol in Australia. Even though the buses that were tested in the diesohol tests used diesohol with the ethanol made from wheat starch waste, our calculations are based on an expected supply of ethanol from molasses from Sarina.

7.5.1 Emissions on a mass per unit energy basis

The results obtained by using the SimaPro life-cycle model along with the upstream and tailpipe emissions data specified in the previous chapters of this report are given in Table 7.8 for the full life cycle for greenhouse gases and criteria pollutants. The upstream emissions and the tailpipe emissions that comprise these totals are given in Table 7.9 and Table 7.10 respectively. The greenhouse gas emissions are graphed in Figure 7.3.

Table 7.8
Urban and total life-cycle emissions (per MJ) calculated for diesel and diesohol

Full Lifecycle	Units	LS Diesel	Diesohol
Greenhouse	kg CO_2	0.0858	0.0800
HC total	g HC	0.140	0.133
HC urban	g HC	0.111	0.106
NOx total	g NOx	1.044	0.966
NOx urban	g NOx	0.987	0.912
CO total	g CO	0.253	0.335
CO urban	g CO	0.242	0.325
PM10 total	mg PM10	40.7	31.8
PM10 urban	mg PM10	39.3	30.5
Energy Embodied	MJ LHV	1.18	1.11

The results separate urban and total emissions. Emissions were assumed to occur in urban areas unless they were produced by a known rural or maritime activity.

The apparent discrepancies in certain values, when compared with tabulations earlier in this report, arise because many of the values that are reported in the main text are in terms of g/MJ measured as usable energy from the engine driveshaft (normally represented as g/kWh), whereas the life-cycle calculations are consistent in setting all the calculations in terms of g/MJ based on the inherent chemical energy of the fuel. On average, this reduces quoted engine dynamometer values by a factor of 3.

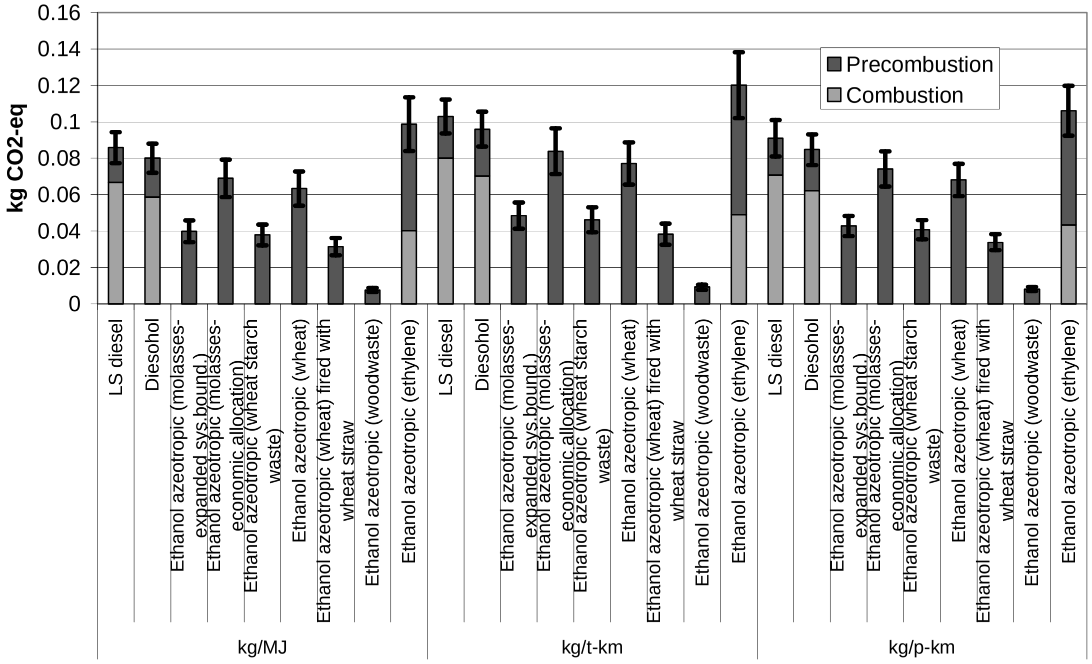

Figure 7.3
Life-cycle emissions of greenhouse gas emissions for low sulfur diesel, diesohol and ethanol.

Table 7.9
Urban and total upstream emissions (per MJ) for diesel and diesohol

Precombustion	Units	LS Diesel (Aus)	Diesohol
Greenhouse	kg CO_2	0.0191	0.0214
HC total	g HC	0.0565	0.0532
HC urban	g HC	0.027	0.026
NOx total	g NOx	0.100	0.103
NOx urban	g NOx	0.043	0.049
CO total	g CO	0.023	0.075
CO urban	g CO	0.012	0.065
PM10 total	mg PM10	5.42	4.97
PM10 urban	mg PM10	4	3.63
Energy Embodied	MJ LHV	1.18	1.11

Table 7.10
Urban and total tailpipe emissions (per MJ) from diesel and diesohol

Combustion	Units	LS Diesel (Aus)	Diesohol
Greenhouse	kg CO_2	0.0667	0.059
HC total	g HC	0.0835	0.080
HC urban	g HC	0.0835	0.080
NOx total	g NOx	0.944	0.863
NOx urban	g NOx	0.944	0.863
CO total	g CO	0.230	0.260
CO urban	g CO	0.230	0.260
PM10 total	mg PM10	35.3	26.82
PM10 urban	mg PM10	35.3	26.82
Energy Embodied	MJ LHV	0	0

7.5.2 Vehicle emissions - trucks (g/km)

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 7.11
Urban and total life cycle emissions (per km) for trucks calculated for diesel and diesohol

Full LC	Units	LS Diesel engine	Diesohol engine
Greenhouse	kg CO_2	0.9250	0.8619
HC total	g HC	1.509	1.430
HC urban	g HC	1.192	1.141
NOx total	g NOx	11.250	10.402
NOx urban	g NOx	10.638	9.823
CO total	g CO	2.723	3.606
CO urban	g CO	2.612	3.501
PM10 total	mg PM10	438.4	342.3
PM10 urban	mg PM10	423.1	327.9
Energy Embodied	MJ LHV	12.7	11.90

Table 7.12
Urban and total precombustion emissions (per km) for trucks calculated for diesel and diesohol

Precombustion		LS Diesel (Aus)	Diesohol
Greenhouse	kg CO_2	0.2060	0.2310
HC total	g HC	0.609	0.573
HC urban	g HC	0.292	0.284
NOx total	g NOx	1.080	1.110
NOx urban	g NOx	0.468	0.531
CO total	g CO	0.243	0.805
CO urban	g CO	0.132	0.700
PM10 total	mg PM10	58.4	53.5
PM10 urban	mg PM10	43.1	39.1
Energy Embodied	MJ LHV	12.7	11.9

Table 7.13
Urban and total tailpipe emissions (per km) for trucks calculated for diesel and diesohol

Combustion		LS Diesel (Aus)	Diesohol
Greenhouse	kg CO_2	0.719	0.631
HC total	g HC	0.900	0.857
HC urban	g HC	0.900	0.857
NOx total	g NOx	10.17	9.292
NOx urban	g NOx	10.17	9.292
CO total	g CO	2.48	2.801
CO urban	g CO	2.48	2.801
PM10 total	mg PM10	380	288.80
PM10 urban	mg PM10	380	288.80
Energy Embodied	MJ LHV	0	0

7.5.3 Vehicle emissions - buses (g/km)

This section gives the calculated values for the emissions from buses, on a per-kilometre basis. The greenhouse gas emissions and the particulate matter emissions are graphed in Figure 7.3.

Table 7.14
Urban and total life-cycle emissions for buses (per km) calculated for diesel and diesohol

Full LC		LS Diesel	Diesohol
Greenhouse	kg CO_2	1.66	1.55
HC total	g HC	2.71	2.57
HC urban	g HC	2.14	2.05
NOx total	g NOx	20.20	18.68
NOx urban	g NOx	19.10	17.64
CO total	g CO	4.89	6.48
CO urban	g CO	4.69	6.29
PM10 total	mg PM10	787	614.62
PM10 urban	mg PM10	760	588.77
Energy Embodied	MJ LHV	22.8	21.37

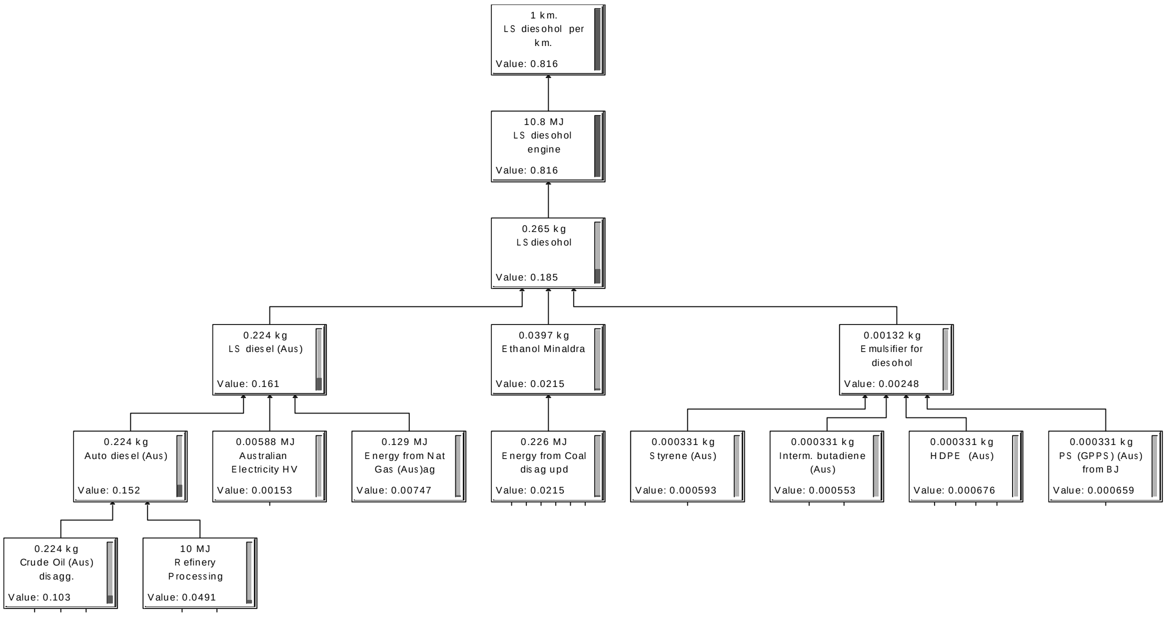

Figure 7.4
Exbodied greenhouse gases emissions (kg CO_2-eq) from diesohol production, processing and use in vehicle

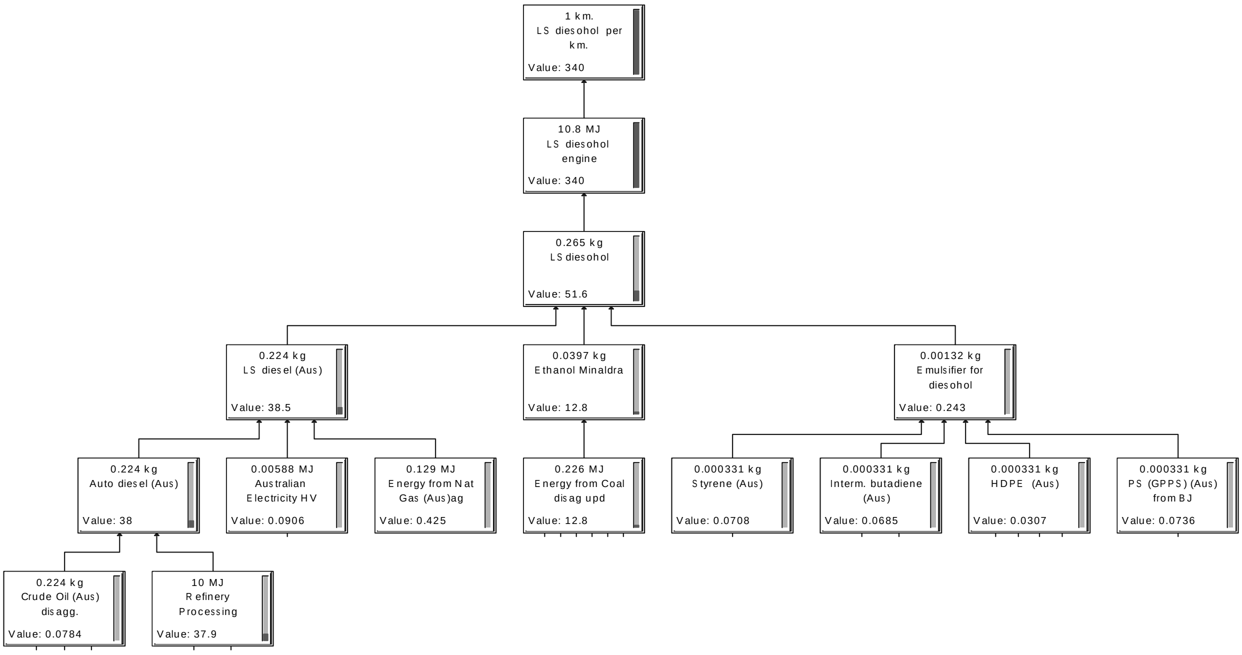

Figure 7.5
Exbodied particulate matter (mg - urban) from diesohol production, processing and use in vehicle

Table 7.15
Urban and total precombustion emissions for buses (per km) calculated for diesel and diesohol

Precombustion		**LS Diesel (Aus)**	**Diesohol**
Greenhouse	kg CO_2	0.37	0.41
HC total	g HC	1.09	1.03
HC urban	g HC	0.52	0.51
NOx total	g NOx	1.94	1.99
NOx urban	g NOx	0.84	0.95
CO total	g CO	0.44	1.45
CO urban	g CO	0.24	1.26
PM10 total	mg PM10	104.9	96.06
PM10 urban	mg PM10	77.4	70.21
Energy Embodied	MJ LHV	22.80	21.37

Table 7.16
Urban and total tailpipe emissions for buses (per km) calculated for diesel and diesohol

Combustion		LS Diesel (Aus)	Diesohol
Greenhouse	kg CO_2	1.29	1.133
HC total	g HC	1.62	1.538
HC urban	g HC	1.62	1.538
NOx total	g NOx	18.26	16.684
NOx urban	g NOx	18.26	16.684
CO total	g CO	4.45	5.030
CO urban	g CO	4.45	5.030
PM10 total	mg PM10	682.31	518.56
PM10 urban	mg PM10	682.31	518.56
Energy Embodied	MJ LHV	0.00	0

7.5.4 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 7.17.

Table 7.17
Estimated one standard deviation uncertainties (in percent) for diesohol emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	10	10
HC	45	17	73
NOx	17	26	8
CO	51	36	66
PM10	45	45	45

7.6 Viability and Functionality

The flash point of the emulsion becomes that of alcohol when the alcohol content exceeds 5% of the volume. Above a 15% ethanol blend an ignition improver is needed, whereas above 25% ethanol engine modifications are required.

Two problems have been found to date with the use of diesohol according to discussions with Mr Ernie Lom and Dr Russell Reeves of APACE Research Ltd. The first of these is comparable to those with the use of low sulfur diesel, and relate to fuel injection equipment components. The components are: i) some T valves fitted to Bosch type feed pumps swell excessively and result in the valve stem becoming jammed; ii) the drive shaft seal fitted to Nipon Denso rotary pumps can swell and soften resulting in fuel leakage; iii) some filter glues, impregnation resins and epoxy resins (such as in DPA pump and RBA transfer pump blades) are susceptible and need to be identified in service.

The second problem, which has been fixed with the installation of booster pumps, concerns the need to ensure that vapour locks do not occur. Adding ethanol changes the vaporization potential of diesel. Evaporative emissions of VOC from vehicles increase when vapour pressure of the fuel is increased or the ambient temp rises (Carnovale et al., 1991). Diesel fuel has a very low vapour pressure but the addition of alcohol to diesel in diesohol creates a fuel with a similar vapour pressure to ethanol. While modern gasoline vehicles have evaporative emissions control measures, diesel vehicles do not. Evaporative emissions may be a significant problem from unmodified vehicles using diesohol, but this needs to be tested. To control evaporative emissions from vehicles using alcohol fuels, measures may need to be implemented to control fuel vapour pressure, and control evaporative emissions from diesel fuel vehicles. APACE Research Ltd ensures that there are no vapour locks by installing a booster pump (E. Lom, pers. comm.).

They also point out that diesohol was the only emulsified fuel to pass stability test conducted by Shell. To date diesohol has been a niche fuel and thus the situation with respect to availability and warranty has not been clarified. During testing of buses using diesohol, the fuel was blended by delivering diesel to Manildra, near Nowra, and blending the diesel with ethanol and emulsifier.

7.7 Health and OHS

7.7.1 Production and transport

The ethanol used in Australia is manufactured from biomass from the fermentation of sugar derived from grain or sugar crops. Production of these feedstock crops results in a range of particles and air toxic emissions.

Feedstock transport to the ethanol production facility results in a range of particles and air toxic emissions. These will be detailed in subsequent work that deals solely with ethanol. In this review of diesohol, these contributions are noted by the difference in value between the last two columns of Table 7.9. This approach is taken because we were specifically asked to compare each fuel (diesohol in this case) against LSD as the reference fuel. Similarly, emissions of particulate matter and air toxics could be expected from the ethanol production process. The process includes high temperature cooking and fermentation, which emits acetaldehyde.

As the composition of diesohol is 85% diesel the production and transport emissions associated with diesohol production are assumed to be similar to LSD, except for the ethanol and emulsfier component. The emulsifier consists of a styrene-butadiene copolymer dissolved in the diesel fuel that, by steric stabilisation, couples with a polyethyleneoxide-polystyrene (PEOPS) copolymer dissolved in the hydrated alcohol. Manufacture of the emulsifier involves butadiene, which is an air toxic. However, the quantities of emulsifier are small (0.5% v/v) compared to the quantities of diesel and ethanol. Consequently the amount of butadiene is very low.

Particulate matter

The urban precombustion (truck) PM10 estimate for LSD is 43 mg/km compared to 39 mg/km for diesohol (Table 7.12).

Air toxics

The urban precombustion (truck) HC estimate for LSD is 0.292 g/km compared to 0.284 g/km for diesohol (Table 7.12). The public health effects of air toxics will be mainly associated with combustion emissions in the large urban centres.

An accompanying disk to this report from provides details of air toxics emissions from upstream activities.

7.7.2 Use

APACE Research results, as summarised in Table 7.5, indicate that compared to LSD emissions, diesohol (E15) emissions have marginally higher CO emissions, but marginally lower NOx and HC emissions.

Particulate matter

The APACE Research results (Table 7.5) indicate that, compared to LSD emissions, diesohol (E15) emissions have lower PM emissions. The values are 0.04 g/MJ (0.25 g/km) for LSD and 0.03 g/MJ (0.19g/km) for diesohol made from low sulfur diesel. The combustion (truck) PM10 estimate from the LCA for LSD is 380 mg/km compared to 289 mg/km for diesohol.

Air toxics

The APACE Research results (Table 7.6) also indicate that compared to LSD emissions, diesohol (E15) emissions have marginally lower acetaldehyde emissions – 0.038 g/km for LSD compared to 0.033 g/km for LSDiesohol (i.e. diesohol made with low sulfur diesel). However, the Swedish Euro2 bus study found emissions of 0.02 g/km acetaldehyde (Ahlvik & Brandberg, 2000) using low sulfur diesel. This provides a measure of the variability in the data and hence the uncertainty in the results.

There are lower formaldehyde emissions using diesohol. Low sulfur diesel emits from 0.014 g/km, whereas LSDiesohol emits 0.011 g/km. Table 7.7 also indicates that acrolein emissions will be lower with diesohol than with diesel fuels.

Information for diesohol was not available for the other air toxics. However the diesohol HC emissions were marginally lower compared to LSD for the APACE Research results. The combustion (truck) HC (assumed to be equivalent to NMVOC) estimate for LSD is 0.900 g/km compared to 0.857 g/km for diesohol.

7.7.3 Diesohol emissions summary

As the composition of diesohol is 85% diesel the production and transport emissions associated with diesohol production are assumed to be similar to LSD. The LCA indicates that urban precombustion PM10 emissions of diesohol (39 mg/km or 3.63 mg/MJ) are marginally lower than LSD (43 mg/km or 4.0 mg/MJ), though the urban precombustion HC emissions are similar at 0.29 g/km or 0.026 g/MJ.

The LCA indicates that combustion PM emissions from diesohol (289 mg/km or 26.8 mg/MJ) are lower than LSD (380 mg/km or 35.3 mg/MJ).

There is limited information available on air toxic emissions for diesohol. The high proportion of diesel in diesohol suggests that the air toxic emissions are unlikely to be substantially different to LSD. The LCA indicates that HC combustion emissions of diesohol are similar to LSD

7.7.4 OHS Issues

The flash point and flammability characteristics of diesohol are those of alcohol. This requires that diesohol be considered and handled as gasoline (petrol) rather than as diesel fuel, even though the flash point of petrol is considerably lower than that of ethanol (13°C). In practical terms, APACE Research handles the fuel as it would ethanol to ensure safety. Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and a moderate irritant.

Occupation exposure of drivers to diesohol vapours during HDV refuelling was assessed by Workcover in 1992 (NSW Workcover Authority, 1999). Normally refuelling is conducted by keeping the fuel dispensing nozzle in the automatic mode with only the last 10-12 litres added manually. The drivers are normally only exposed to diesohol vapours during manual refuelling. The results indicate that levels of diesohol vapours are low and do not represent a significant health hazard to drivers.

7.8 Environmental Issues

The present use of ethanol, as in diesohol, is that of a niche fuel. As such, there are no issues related to sustainability. However, if ethanol were to become a dominant fuel then it would have to be based on ligno-cellulose. Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia's oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia's croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large-scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

The environmental impact from the production of diesohol are the same as those from the production of the diesohol feedstocks; namely diesel as ethanol, and will be dealt with in the relevant chapters.

In particular, we draw attention to the fact that appropriate disposal of the refinery waste-products is crucial to environmental impacts or benefits. Dunder application is often criticised as being the cause of poor waste quality in Queensland, though there is little evidence of this (www.sunfish.org.au/fishkills/fishkills.htm). Conversely, appropriate and careful disposal of dunder means that many farmers in the district near Sarina now use it as a fertiliser and soil condition - even though it was once considered a poison.

We are not aware of any issues related to groundwater contamination.

7.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 7.18 lists the estimated emissions factors for diesohol. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of diesohol. The estimates of Arcoumanis (2000) indicate that diesohol can be expected to meet all future Australian Design Rules for all pollutants except total hydrocarbon which may be slightly above Euro3 and Euro4 standards.

Table 7.18
Estimated relative emission factors for diesohol under future technologies.
Euro2 diesel (shown in bold) are taken as 1.0

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	1.1	**1.0**	1.1	**1.0**	0.8	**1.0**	0.6	**1.0**	0.9
Euro3	**0.53**	0.5	**0.6**	0.7	**0.71**	0.6	**0.67**	0.4	**1.0**	0.9
Euro4	**0.38**	0.4	**0.42**	0.5	**0.5**	0.4	**0.2**	0.1	**1.0**	0.9

APACE Research advises that vapour lock problems had led to higher THC and CO emissions as reflected in Arcoumanis (2000). APACE has indicated that the addition of a booster pump now overcomes vapour lock problems and the resulting THC and CO problems. This means that LSdiesohol should be able to meet future ADRs.

7.10 Summary

7.10.1 Advantages

- As a partly renewable fuel it produces less fossil CO_2 than conventional fuels.
- Particulate emissions are lowered.
- 1,3 butadiene and benzene levels decrease as the ethanol concentration increases.
- Lower sulfur content than conventional diesel.

7.10.2 Disadvantages

- Overseas, the chemical emulsifiers used to blend ethanol and diesel contain harmful chemicals. According to APACE the chemical emulsifier that they use is composed only of hydrocarbons and oxygen and is thus no more harmful than diesel fuel.

7.11 Appendix to Diesohol Fuel Chapter

This appendix (Appendix 6) comprises a separate file of scanned material provided by APACE.

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8. Compressed Natural Gas

8.1 Background

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH_4), and is produced either from gas wells or in conjunction with crude oil production. The composition of natural gas used in Melbourne in 1997/98 was 91.6 percent methane, 5.0 percent ethane, 0.4 percent propane, 0.1 percent butane, 0.8 percent nitrogen and oxygen, and 2.1 percent carbon dioxide. Natural gas is consumed in the residential, commercial, industrial, and utility markets.

The interest for natural gas as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it is stored onboard a vehicle in a compressed gaseous state (CNG), though it is also possible to liquefy it and store it in liquid form (LNG).

In Australia, CNG is compressed to around 25 MPa for on-board storage at typically 20 MPa. Refuelling of CNG vehicles is done in the following way. Natural gas is drawn from the distribution network, compressed to 25 MPa and stored in pressure vessels. When a vehicle is being filled and pressure in the storage vessel drops, the compressor draws further gas from the pipeline. The storage vessels are used only to speed up the filling process, not to hold large quantities of compressed gas. In some cases, for example ‘slow-fill’ refuellers, the pressure vessel stage is bypassed and the compressor compresses gas directly into the cylinder of the vehicle.

8.1.1 Natural gas production

Natural gas consumed in Australia is domestically produced. Gas streams produced from reservoirs contain natural gas, liquids and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids. The separated gas is further processed to meet specified requirements. For example, natural gas for transmission companies must generally meet certain pipeline quality specifications with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen-sulfide content. A dehydration plant controls water content; a gas processing plant removes certain hydrocarbon components to hydrocarbon dewpoint specifications; and a gas sweetening plant removes hydrogen sulfide and other sulfur compounds (if present). As raw natural gas is odourless, a chemical odorant (generally sulfur in the form of a mercaptan) is generally added prior to entering the local distribution system to enable expeditious identification of any gas leaks, although some gas is transmitted without odorant.

8.1.2 Natural gas market

Natural gas is distributed throughout Australia in pipeline systems (Figure 5.1) that extend from the well-head to the end user.

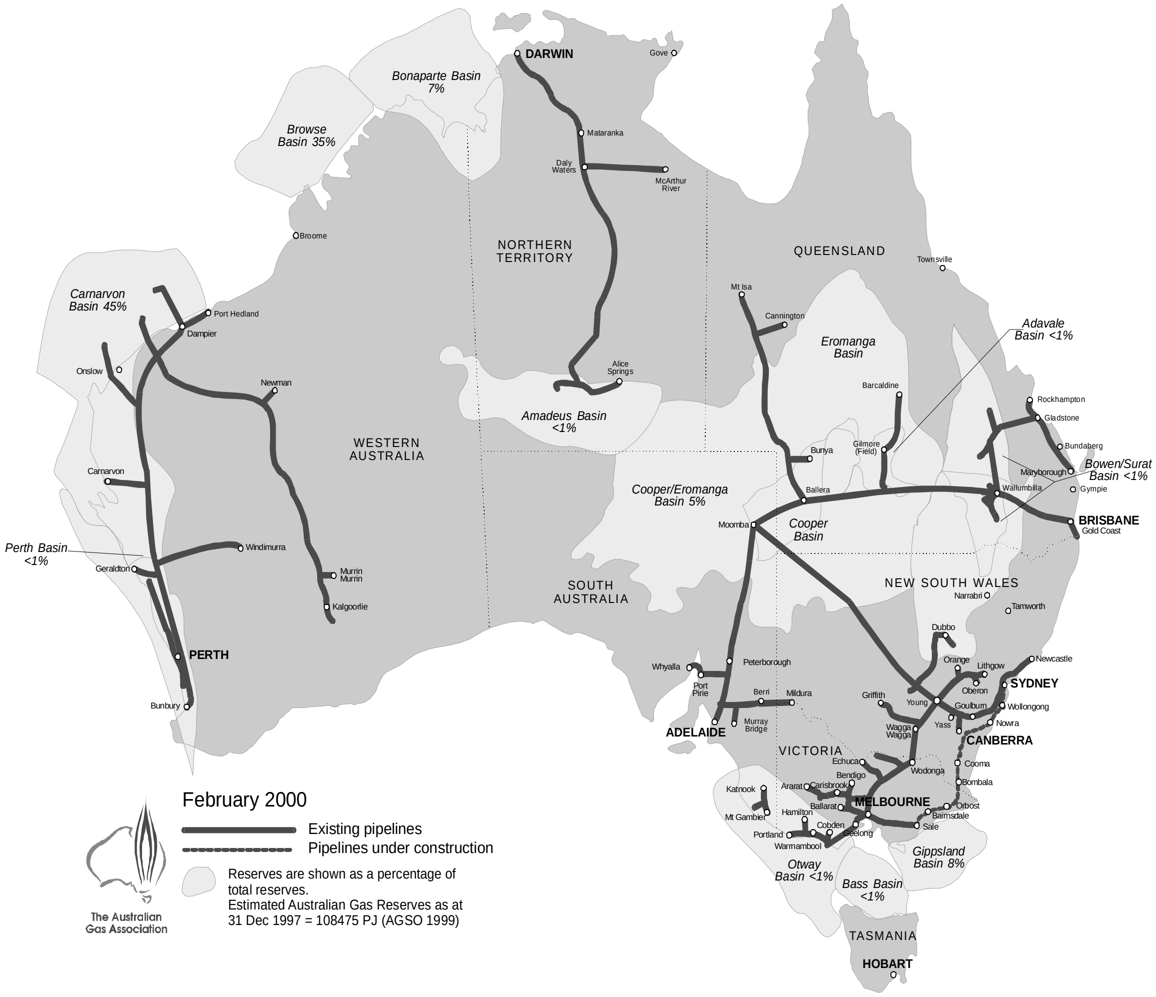

Figure 8.1
Australian gas fields and pipelines

Every mainland State and Territory has access to natural gas through pipelines. The pipeline system consists of long-distance transmission systems, followed by local distribution systems. Some underground storage is also used to help supply seasonal peak needs.

The Australasian Natural Gas Vehicles Council web site in their submission for this study point out that:

> Known world reserves of natural gas now constitute over 95% of equivalent oil reserves. In Australia this ratio is more than three times the oil reserve. Proven Australian resources of natural gas currently stand at 109,051 PJ, at existing production levels, this will last 91 years compared to domestic oil reserves which are estimated to last 39 years. Historically, reticulated gas with most of the infrastructure being below ground, has survived most disasters including two world wars. Natural gas is abundant, clean, readily accessible and strategically independent of traditional oil based fuels. The last point is important in that NG is not controlled by a small number of global corporations and cartels and is not reliant on USD exchange rates or world parity pricing.

8.1.3 Fuel characteristics

Natural gas has very different fuel characteristics from the fuels normally used in internal combustion engines. Its density, at 0.70 g/L is lighter than air. Louis (2001) cites a lower heating value of 52.9 MJ/kg.

The energy content (higher heating value) of CNG varies from 38.8 megajoules per cubic metre at atmospheric pressure in New South Wales and South Australia to 38.5 in Victoria, 37.5 in Western Australia and 41.9 in the Northern Territory (National Greenhouse Inventory Committee, 1998)). The average energy content is similar to that of one litre of automotive diesel oil (38.6 megajoules), and about 12 per cent above that of one litre of gasoline (34.2 megajoules) (ABARE, 1991). Pressurised storage of a cubic metre of natural gas as CNG, however, requires a container volume of 4 to 5 litres.

A national fuel standard for CNG is to be developed in 2001-2002 under the *Fuel Quality Standards Act 2000.*

8.1.4 Implications for engine conversions

Because of its characteristics, natural gas can be used in spark ignition engines, but in compression ignition engines a proportion of diesel fuel is usually required to trigger ignition. Alternatively, diesel engines can be converted to spark ignition for natural gas use.

For diesel engines (primarily HDVs in Australia), the conversion to a compression ignition dual (mixed) fuel configuration involves use of a pilot supply of diesel to ignite the natural gas. This requires the addition of a gas fuel system alongside the existing diesel fuel system, together with a mechanism for regulating the proportion of diesel and gas for the engine speed and load conditions. According to the IEA (1993) engine efficiency for this configuration is about the same as that for a diesel engine. BTCE (1994) states that the efficiency of dual (mixed) fuel systems can be equal to or higher than for diesel at high loads, but lower at part loads. For this reason, the overall efficiency in service is lower than for diesel. This chapter deals with single fuel vehicles so that dual fuel vehicles have not been examined. It is to be expected, based on results of LPG dual fuel vehicles, that emissions reductions from dual fuel vehicles will not be as large as those from single fuel vehicles.

Conversion of diesel engines to spark ignition engines running solely on natural gas requires more extensive modification, in that the diesel fuel injectors in the cylinder head will be replaced by spark plugs, and an ignition system added to the engine. A compression ratio lower than that of the diesel is likely to be required. Also, a larger cylinder capacity than that required for a dual (mixed) fuel system may be needed, to provide the same energy content. Though conversions have been the primary source of natural gas engines in Australia to date, increasing availability of OEM engines and vehicles makes conversions less relevant.

8.2 Full Fuel Cycle

Nigge (2000) recently undertook a detailed life cycle assessment of natural gas vehicles in Germany that quantified emissions and health effects.

8.2.1 Tailpipe

The Australasian Natural Gas Vehicle Council (ANGVC) kindly provided emissions data from the latest generation of engines taken from various studies including UK test data on a Scania CNG 113M engine using Mobil CNG (Table 8.1), data from Cummins on their 8.3 litre diesel and C8.3G engine with and without catalyst (Lyford-Pike, 2001) and data from a 9.8 L Transcom modified Renault 620-45 natural gas engine (AEC Limited), as well as data from South Australian CNG buses (ANGVC, 2001).

Table 8.1
Scania diesel and CNG test results (g/kWh) in the UK (Andrew, 2001)

	HC	CO	NOx	PM	CO_2
Diesel	0.864	1.442	7.014	0.373[1]	756.3
CNG	0.212	0.018	0.962	0.007	674
LNG	0.18	0.017	1.532	0.013	698

Table 8.1 provides results of tests of the present generation of diesel engines (Scania DSC 11-21) as tested at the Millbrook Proving Ground in January 2001 (Andrew, 2001). The drive cycle was not specified. However, as the European Community requires Euro3 standards for heavy vehicles as from January 2000, we expect that both the engines and the test regime corresponded to Euro3. The specific fuel consumption during the test of the CNG vehicle was 190 g/kWh at 1100 to 1800 rpm. The minimum range of the CNG truck was 560 km. The truck achieved a range in excess of 640 km by increasing the CNG pressure from 20 MPa to 25 MPa

Table 8.2 provides results obtained in December 2000 by a Renault engine tested under the European Transient Cycle (ETC), and by Cummins engines tested in November 2000 under the US EPA 99/00 requirements. These are equivalent to ADR 80 and to Euro3 requirements.

Table 8.2
Emissions results (g/kWh) for Renault and Cummins engines

	NMHC	THC	CH_4	NOx + NMHC	CO	NOx	PM	CO_2
Transcom modified Renault 620-45 with catalyst	0.003	0.531			0.024	2.432		
Cummins (C8.3G) CNG with catalyst (ULEV)	0.28		6.27	2.33	1.04	2.05	0.01	678
Cummins (C8.3G) CNG without catalyst (LEV)	1.058		6.54	3.63	8.67	2.57	0.034	695
Cummins Diesel (ISC280) with catalyst					0.67	5.36	0.07	700
Cummins Diesel (ISC280) without catalyst					1.21	5.36	0.12	753

By contrast, Table 8.3 gives the emission results of tests on a MAN NL 202 bus with a D0826 LUH, 6.87 litre, turbocharged, intercooled engine, and with a D2866 DUH, 11.97 litre natural gas engine. These engines are on buses that are actually in service at present. The tests were done using the ECE R-49 cycle. The diesel engines were tested with diesel fuel (2000 ppm), low sulfur diesel (500 ppm) and with Euro3 diesel (300 ppm sulfur).

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[1] This value is unduly large. Our subsequent calculations are based on the LSD value for PM in Table 8.3.

Table 8.3
South Australian bus emissions data (g/kWh)

	HC	CO	NOx	PM
Euro 1 Diesel	0.25	0.97	7.8	0.17
Euro 2 Diesel (LSD)	0.13	0.48	6.66	0.10
Euro 3 Diesel	0.04	0.65	4.87	0.08
CNG	0.2	1	1	0.02

One problem with certification procedures based on engine dynamometers is that they may report values that substantially differ from those calculated by chassis dynamometers. The NSW EPA (Brown et al. 1999) also tested Scania 11L Turbo Euro2 technology CNG buses for their performance with, and without, a catalyst. The results are reproduced in Table 8.4.

Table 8.4
Methane and non-methanic hydrocarbon emissions (g/kWh) from CNG buses

		THC	Methane	NMVOC
Without catalyst	Bus #1	2.86	2.64	0.22
Without catalyst	Bus #2	3.37	2.92	0.45
With catalyst	Bus #1	1.88	1.85	0.03
With catalyst	Bus #2	3.02	2.78	0.24

Another source of representative data is given in Table 8.5, which reproduces the emission factors (based on emissions per MJ of fuel use) for heavy vehicles fuelled by natural gas that are given by the National Greenhouse Gas Inventory Committee (1998). Using these default figures typical methane emission are 2.5 g/km and the N_2O emissions for a natural gas-fuelled urban bus are 0.0247 g/km.

Table 8.5
Emission factors (g/MJ) for heavy vehicles fuelled by natural gas

Gas	Emission factor
CO_2	54.4
CH_4	0.101
N_2O	0.001
NOx	1.2
CO	0.2
NMVOC	0.01

We note that the estimate of tailpipe emissions of 1344 g CO_2/km for a CNG bus that Beer et al. (2000) obtained corresponds to a fuel efficiency of 24.7 MJ/km. As a typical energy content for natural gas is 39 MJ/m^3 the results of Beer et al. (2000) were based on an assumed fuel economy of 1.58 km/m^3. According to NSW State Transit (Hardy, pers. comm. 2000) the known fuel consumption of the CNG buses is 1.6 km/m^3. The results of Andrew (2001) that were used in this analysis indicate that the present generation of CNG buses are far more fuel efficient, emitting 595 g CO_2/km, which corresponds to a fuel efficiency of 10.9 MJ/km.

8.2.2 Upstream emissions

As CNG is assumed to be produced from high pressure gas supplies in major cities, standard gas production and transmission processes are used for the upstream emissions of Natural Gas. Added to this are compression processes based on either a gas engine driven CNG compressor, or an electrically driven CNG compressor.

Data on natural gas production have been derived from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000). This data is presented in Table 8.6.

Table 8.6
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use	Production 1998	Energy use to energy production ratio
		PJ	PJ	GJ/PJ produced
Oil and gas production and field processing	Petroleum	0.9	2528.6	0.36
	Gas	141.1	2528.6	55.80
Natural gas transmission	Gas	8.6	688.5	12.49
Gas production and distribution	Gas	2.4	371.5	6.46

The compression process involves a simple model with natural gas as energy as the main inputs, and CNG as the main output. The energy use is usually quoted in terms of its efficiency compared with the energy value of the gas being compressed. Data on compression are taken from Wang (1999) and are listed in Table 8.7. The emission data for natural gas combustion for compression is taken from standard natural gas combustion data for industrial boilers presented in NGGIC (2000) for greenhouse emissions and in Environment Australia (1999) for air toxics. This data is presented in Table 8.8. The data for electricity combustion are from the same sources for emissions while fuel usage and grid mix are taken from Electricity Supply Association of Australia (2000). Full fuel cycle inputs are presented in Table 8.9 and FFC emissions are presented in Table 8.10 for an average Australian grid mix.

Table 8.7
Energy use in natural gas compression for two fuel scenarios

Fuel	Efficiency	Value in MJ	Comment
Energy from Natural Gas	91.70%	4643	90.5 MJ per 1000MJ Gas (51.3MJ/kg) compressed
Australian Electricity	96.60%	1550	30.2 MJ per 1000MJ Gas (51.3MJ/kg) compressed

Table 8.8
Air emissions from combustion of 1 MJ of natural gas for process energy

Emissions	Value	Unit	Source
CO_2	51.19	g	NGGIC, 1997 Standard data Table 1
methane	10.41	mg	NGGIC, 1997 Standard data Table 1
N_2O	0.12	mg	NGGIC, 1997 Standard data Table 1
NOx	220.59	mg	NGGIC, 1997 Standard data Table 1
CO	42.32	mg	NGGIC, 1997 Standard data Table 1
non methane VOC	3.48	mg	NGGIC, 1997 Standard data Table 1
SOx	0.053	mg	(Environment Australia 1999)
particles	3.078	mg	(Environment Australia 1999)
benzene	0.86	µg	(Environment Australia 1999)
formaldehyde	30.38	µg	(Environment Australia 1999)
n-Hexane	734.18	µg	(Environment Australia 1999)
toluene	1.37	µg	(Environment Australia 1999)
PAHs	0.28	µg	(Environment Australia 1999)
As	0.08	µg	(Environment Australia 1999)
Be	0	µg	(Environment Australia 1999)
Cd	0.46	µg	(Environment Australia 1999)
Chromium	0.56	µg	(Environment Australia 1999)
cobalt	0.03	µg	(Environment Australia 1999)
Copper	0.35	µg	(Environment Australia 1999)
Lead	0.2	µg	(Environment Australia 1999)
manganese	0.15	µg	(Environment Australia 1999)
mercury	0.11	µg	(Environment Australia 1999)
Nickel	0.86	µg	(Environment Australia 1999)
Selenium	0.01	µg	(Environment Australia 1999)
Zn	11.65	µg	(Environment Australia 1999)

Note: these figures are not for a full fuel cycle – energy input to supply gas for combustion are shown in Table 8.6.

Table 8.9
Fuel inputs for 1 MJ of average Australian electricity

Resources (Inputs from Nature)		
coal 19.5MJ/kg	7.22	g
coal 22.1MJ/kg	28	g
coal 22.6MJ/kg	40	g
crude oil	210	mg
lignite 14.4MJ/kg	4.81	g
lignite 8.2MJ/kg	108	g
natural gas	40.9	mg
pot. energy hydropower	114	kJ

Source: Grant, unpublished data from Life Cycle Inventory Databases

8.2.3 Fugitive emissions

Natural gas can contain significant quantities of naturally occurring CO_2, which in the past has often been vented to the atmosphere at the well-head. Le Cornu (1989) pointed to Cooper Basin gas as having up to 35 per cent by weight (12.7 per cent by volume) of naturally occurring CO_2. On a state by state basis, vented CO_2 accounts for between 3 and 15 per cent of full fuel-cycle CO_2 emissions from natural gas combustion (Wilkenfeld, 1991). In some instances CO_2 recovered from natural gas could be compressed and used in enhanced oil recovery.

Fugitive emissions of methane occur at the wellhead (production), processing, transmission and end user distribution. Our analysis indicates that average emissions at production stage in Australia amount to 2.17 kg per tonne of gas, while processing contributes 5.74 kg per tonne of gas.

Australian long distance high pressure (up to 15 MPa) transmission pipelines are relatively modern (the oldest dates back to 1969) and built to high standards. They are well maintained and accidental leaks are a rarity. It is estimated that at transmission stage fugitive emissions are 0.005% of the total network throughput.

Most gas losses from the distribution systems are by way of leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters. It is estimated that emissions from the distribution network, called unaccounted gas, i.e. the difference between the gas issued by the utilities and the gas sold to customers may be as high as 7.5% (NGGIC, 1996). We consider this to be an upper bound to likely fugitive emissions.

Table 8.10
Air emissions for 1 MJ of average Australian electricity

Emission	Value	Unit	Emission	Value	Unit
acetaldehyde	54.4	µg	Manganese	82.2	pg
antimony	1.69	µg	Methane	332	mg
As	39.4	µg	Methane(sea)	45.7	µg
B	6.47	µg	methyl ethyl ketone	37.5	µg
Ba	115	Ng	Methyl isobutyl ketone	15	µg
Be	2.06	µg	Methyl methacrylate	1.87	µg
benzene	125	µg	Mg	617	µg
benzene sea	69.7	Pg	Mn	47	µg
benzo(a)pyrene	683	Pg	Mo	152	ng
Bi	985	Pg	N_2O	2.77	mg
Carbon disulfide	12.2	µg	naphthalene	267	ng
Cd	4.87	µg	n-Hexane	933	ng
Chloroform	5.62	µg	n-hexane (sea)	59	ng
CO	60.4	Mg	Ni	26.3	µg
CO (sea)	5.75	µg	Nickel	1.07	ng
CO_2	253	G	non methane VOC	7.49	mg
cobalt	16.5	Pg	Non methane VOC (sea)	17.5	µg
Copper	255	Pg	NOx	678	mg
Cr (III)	24.4	µg	NOx (sea)	18.4	µg
Cr (VI)	4.49	µg	o-xylene	9.98	pg
Cu	69.2	Ng	o-xylene (sea)	0.182	pg
cumene	506	Ng	PAH	2.01	µg
CxHy sulfur	4.31	Ng	PAH (sea)	24.7	pg
Cyanide	487	µg	Pb	39.7	µg
cyclohexane	17.2	Ng	pentane	3.13	µg
DEHP	6.94	µg	phenol	1.5	µg
Dibutyl phthalate	5.25	µg	PM10	15.4	mg
Dioxin & Furans	165	Pg	PM10 (sea)	83.1	pg
dust	18.5	Mg	Se	73	µg
ethylbenzene	10.2	µg	Selenium	68.6	pg
ethylbenzene (sea)	0.104	Pg	Soot	57.4	µg
F	14.4	Mg	SOx	1.26	g
formaldehyde	32.5	µg	styrene	2.44	µg
formaldehyde (sea)	2.5	Ng	tetrachloroethylene	4.12	µg
H_2S	39.4	Ng	toluene	29.9	µg
HCl	113	Mg	toluene (sea)	122	pg
hexane	6.37	µg	Trichloroethylene	5.81	µg
Hg	4.73	µg	V	902	ng
Lead	316	Pg	xylenes	3.6	µg
Li	65.5	Pg	Zn	123	ng

The values for fugitive emissions used in this study are based on data on fugitive emission from natural gas production and also from the NGGI for 1998. The values are presented in Table 8.11.

Table 8.11
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO_2	CH_4	N_2O	NOx	CO	NMVOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	1257	14.8	0.2				0.1
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for Oil and Gas Production	Venting at Gas processing plant	1272	2814	119.6				42.3
	Distributed Venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

A process tree for CNG production is shown in Figure 8.2 with the methane emission shown in grams as the lower value in each process box. The largest fugitive emission is in the assumed loss in fuel distribution, which is discussed in more detail below.

Methane emissions from vehicles

Methane, the principal component of natural gas, has a greenhouse radiative forcing (GWP) of 21 over a 100-year period. It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

As methane is a non-reactive hydrocarbon, tailpipe emissions of methane are not as well controlled by catalytic converters. According to Nylund and Lawson (2000: p.46) the sulfur based odorant used in natural gas at very low concentration levels can have a very detrimental effect on the conversion efficiency of oxidation catalysts, bringing their methane conversion down to 30%. When catalysts are optimised for methane, then conversion efficiencies can be as high as 85-90%.

Methane fugitive losses in distribution

Fugitive losses would have the potential to reduce substantially any advantages that natural gas may have in terms of emissions. Gas supply authorities considered that fugitive losses would be less than 2 per cent, and concentrated entirely on the old town-gas reticulation systems. Refuelling depots or retail gas reticulation systems would be serviced by new medium or high pressure lines, and fugitive losses from this form of distribution might be expected to be very low. BTCE (1994) point out that fugitive losses may be exaggerated through a lack of understanding of the term ‘unaccounted for gas,’ which is the overall accounting error including metering over a vast distribution network.

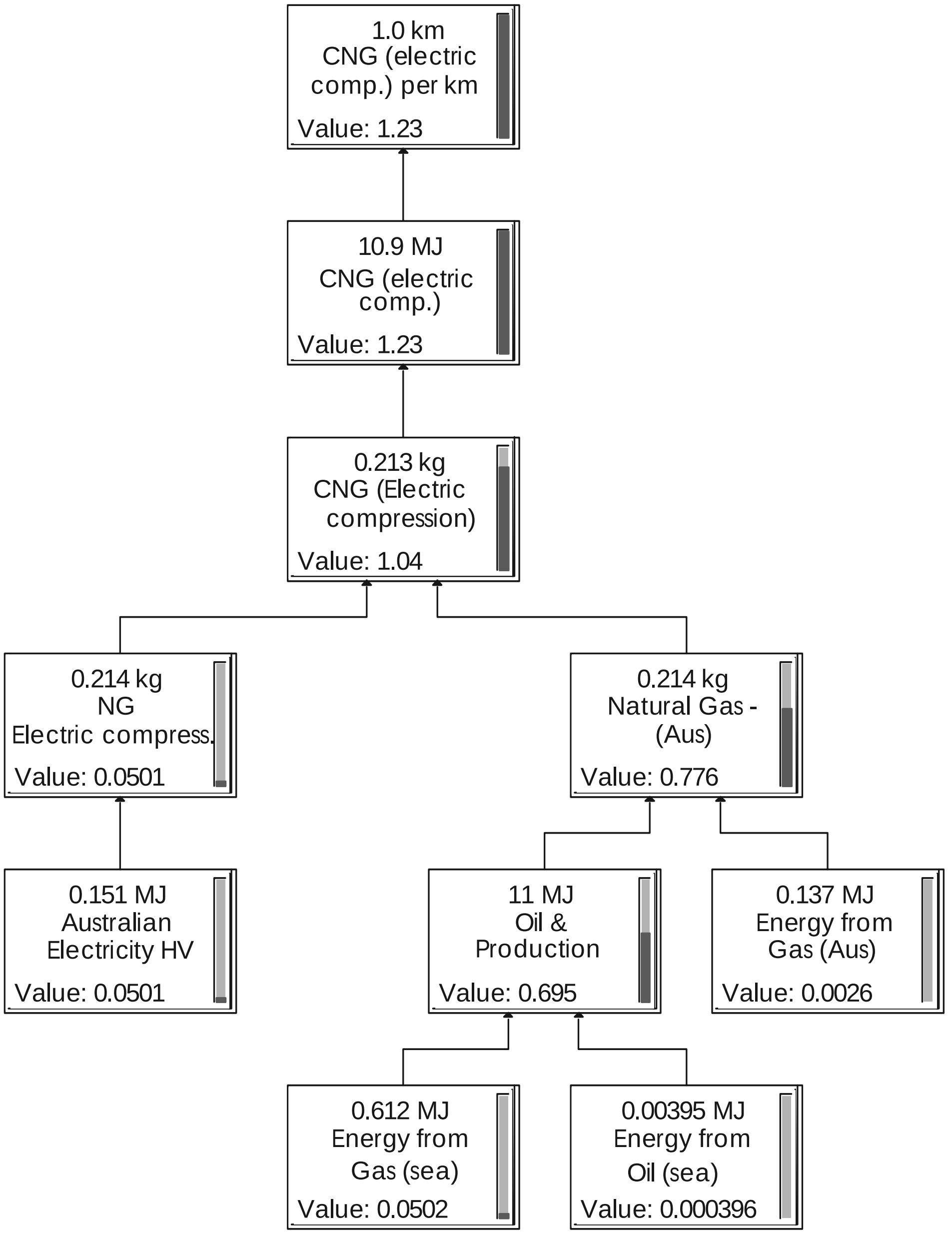

Figure 8.2
Methane emission in grams across CNG life cycle per km truck transport

(Kadam, 1999) assumes emissions from gas processing plants are 0.1% while the 1998 NGGI claims total distribution losses for low pressure gas supply are 0.25%. In the final modelling, a figure of 0.1% has been used for fugitive emission of methane from CNG facilities – including all operations from the point of gas supply to the facility, up to, but not including, the combustion of the gas on board the vehicle. A sensitivity analysis showing the effect of different levels of fugitive emissions is presented in Figure 8.3. It shows that up to 1% emission the greenhouse gas emission results are still lower than the baseline diesel fuel, though at 10% the full fuel cycle emission is substantially above the diesel baseline. The exbodied emissions and the baseline are the same at approximately 4% fugitive emissions.

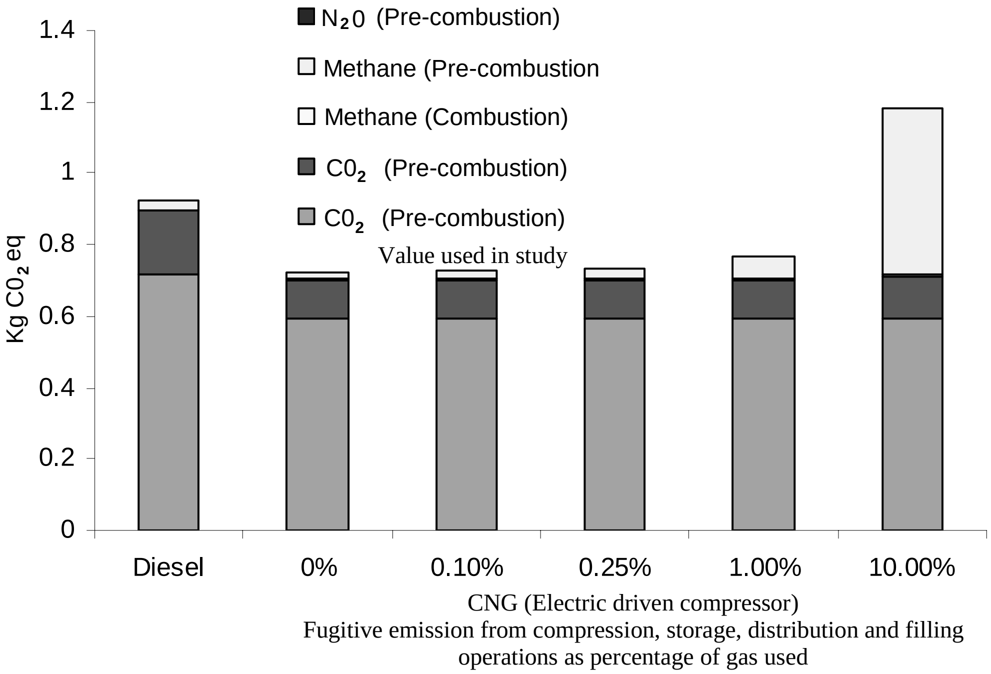

Figure 8.3
Effect of different fugitive emission assumption of full fuel cycle greenhouse emission per km of truck travelled

Two modes of compression were examined: compression using natural gas and compression using electricity.

8.3 Results

8.3.1 Emission per unit energy

Table 8.12
Urban and rural life cycle emissions calculated for diesel and CNG

Full Lifecycle	Units (per MJ)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.0858	0.0665	0.0683
NMHC total	g HC	0.140	0.027	0.029
NMHC urban	g HC	0.111	0.003	0.003
NOx total	g NOx	1.044	0.140	0.152
NOx urban	g NOx	0.987	0.126	0.137
CO total	g CO	0.253	0.011	0.014
CO urban	g CO	0.242	0.005	0.008
PM10 total	mg PM10	40.7	1.1	1.2
PM10 urban	mg PM10	39.3	0.9	1.0
Energy Embodied	MJ LHV	1.18	1.09	1.15

Table 8.13
Urban and rural precombustion emissions per MJ for CNG

Precombustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.0191	0.0117	0.0135
NMHC total	g HC	0.0565	0.0248	0.0273
NMHC urban	g HC	0.027	0.001	0.001
NOx total	g NOx	0.100	0.026	0.038
NOx urban	g NOx	0.043	0.013	0.023
CO total	g CO	0.023	0.007	0.011
CO urban	g CO	0.012	0.001	0.004
PM10 total	Mg PM10	5.42	0.439	0.526
PM10 urban	Mg PM10	4	0.257	0.327
Energy Embodied	MJ LHV	1.18	1.09	1.15

Table 8.14
Urban and rural combustion emissions per MJ for CNG

Combustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.067	0.054	0.054
NMHC total	g HC	0.084	0.019	0.019
NMHC urban	g HC	0.084	0.019	0.019
NOx total	g Nox	0.944	0.114	0.114
NOx urban	g Nox	0.944	0.114	0.114
CO total	g CO	0.230	0.003	0.003
CO urban	g CO	0.230	0.003	0.003
PM10 total	mg PM10	35.26	0.7	0.7
PM10 urban	mg PM10	35.26	0.7	0.7
Energy Embodied	MJ LHV	0	0	0

Table 8.15
Summary of life cycle emissions per MJ from CNG

		LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	Precombustion	0.0191	0.0117	0.0135
Greenhouse	Combustion	0.0667	0.0548	0.0548
NMHC total	Precombustion	0.0565	0.0248	0.0273
NMHC total	Combustion	0.0835	0.0019	0.0019
NMHC urban	Precombustion	0.0271	0.0007	0.0010
NMHC urban	Combustion	0.0835	0.0019	0.0019
NOx total	Precombustion	0.1000	0.0262	0.0384
NOx total	Combustion	0.944	0.114	0.114
NOx urban	Precombustion	0.043	0.013	0.023
NOx urban	Combustion	0.944	0.114	0.114
CO total	Precombustion	0.0225	0.0072	0.0108
CO total	Combustion	0.2301	0.0034	0.0034
CO urban	Precombustion	0.0123	0.0014	0.0045
CO urban	Combustion	0.2301	0.0034	0.0034
PM10 total	Precombustion	5.42	0.44	0.53
PM10 total	Combustion	35.26	0.66	0.66
PM10 urban	Precombustion	4.00	0.26	0.33
PM10 urban	Combustion	35.26	0.66	0.66
Energy Embodied	Precombustion	1.18	1.09	1.15

8.3.2 Emissions per unit distance

Table 8.16
Urban and rural life cycle emissions per km calculated for diesel, CNG

Full Lifecycle	Units (per km)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.9250	0.7284	0.7474
NMHC total	g HC	1.509	0.293	0.320
NMHC urban	g HC	1.192	0.028	0.032
NOx total	g NOx	11.250	1.533	1.666
NOx urban	g NOx	10.638	1.383	1.502
CO total	g CO	2.723	0.116	0.155
CO urban	g CO	2.612	0.052	0.086
PM10 total	mg PM10	438.4	12.0	12.9
PM10 urban	mg PM10	423.1	10.0	10.7
Energy Embodied	MJ LHV	12.7	11.90	12.50

Table 8.17
Urban and rural precombustion emissions per km for diesel and CNG

Precombustion	Units (per km)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.2060	0.1290	0.1480
NMHC total	g HC	0.609	0.272	0.299
NMHC urban	g HC	0.292	0.007	0.011
NOx total	g NOx	1.080	0.287	0.420
NOx urban	g NOx	0.468	0.137	0.256
CO total	g CO	0.243	0.079	0.118
CO urban	g CO	0.132	0.015	0.049
PM10 total	mg PM10	58.4	4.81	5.76
PM10 urban	mg PM10	43.1	2.81	3.58
Energy Embodied	MJ LHV	12.7	11.9	12.5

Table 8.18
Urban and rural combustion emissions per km for diesel, CNG

Combustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO_2	0.719	0.595	0.595
NMHC total	g HC	0.900	0.212	0.212
NMHC urban	g HC	0.900	0.212	0.212
NOx total	g NOx	10.177	1.246	1.246
NOx urban	g NOx	10.177	1.246	1.246
CO total	g CO	2.480	0.037	0.037
CO urban	g CO	2.480	0.037	0.037
PM10 total	mg PM10	380.00	7.2	7.2
PM10 urban	mg PM10	380.00	7.2	7.2
Energy Embodied	MJ LHV	0	0	0

Table 8.19
Summary of life cycle emissions per km for diesel, CNG

		LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	Precombustion	0.2060	0.1290	0.1480
Greenhouse	Combustion	0.7190	0.5994	0.5994
NMHC total	Precombustion	0.6090	0.2720	0.2990
NMHC total	Combustion	0.9000	0.0212	0.0212
NMHC urban	Precombustion	0.2920	0.0072	0.0108
NMHC urban	Combustion	0.9000	0.0212	0.0212
NOx total	Precombustion	1.0800	0.2870	0.4200
NOx total	Combustion	10.170	1.246	1.246
NOx urban	Precombustion	0.468	0.137	0.256
NOx urban	Combustion	10.170	1.246	1.246
CO total	Precombustion	0.2430	0.0788	0.1180
CO total	Combustion	2.4800	0.0368	0.0368
CO urban	Precombustion	0.1320	0.0154	0.0488
CO urban	Combustion	2.4800	0.0368	0.0368
PM10 total	Precombustion	58.40	4.81	5.76
PM10 total	Combustion	380.00	7.17	7.17
PM10 urban	Precombustion	43.10	2.81	3.58
PM10 urban	Combustion	380.00	7.17	7.17
Energy Embodied	Precombustion	12.70	11.90	12.50

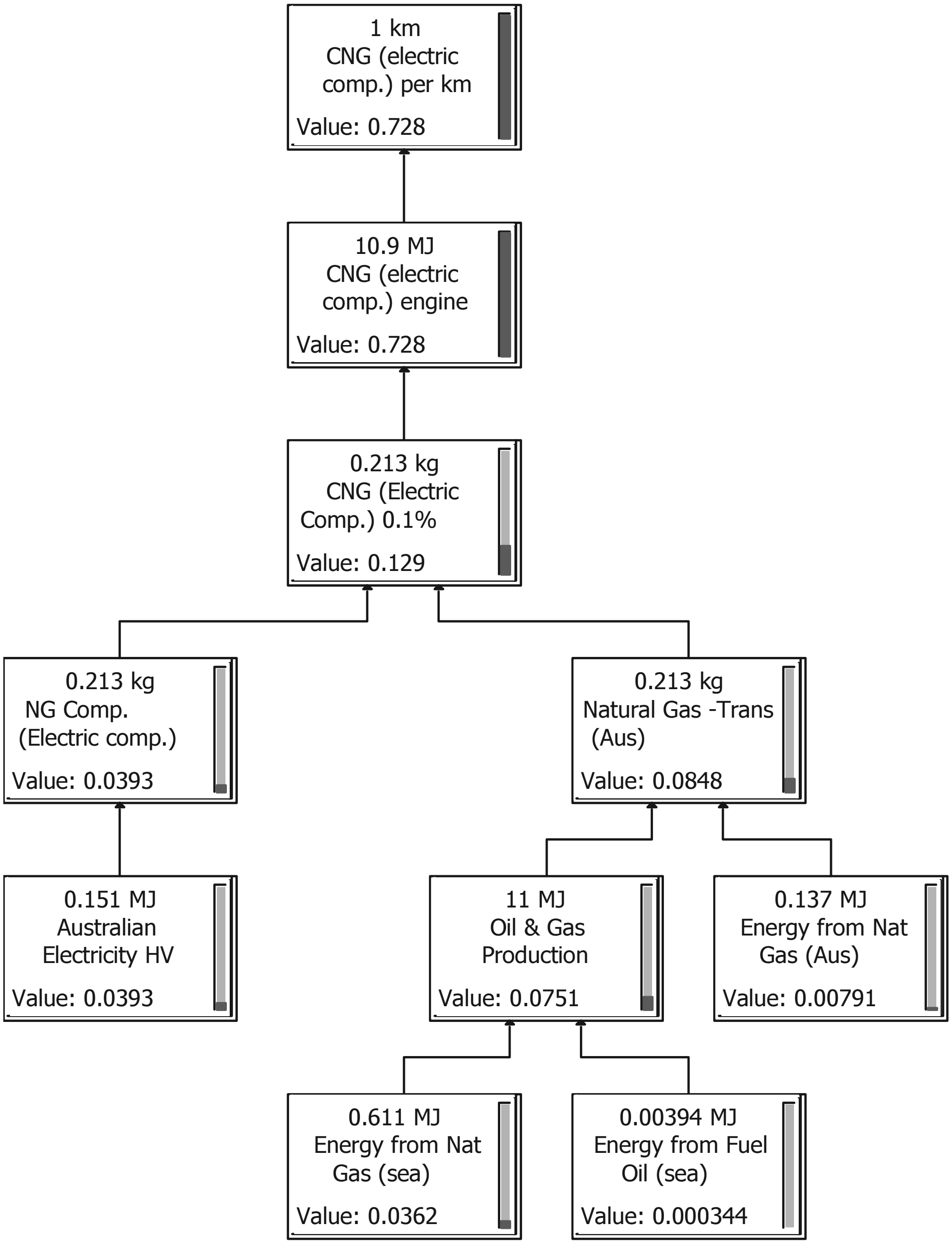

Figure 8.4
Exbodied greenhouse gases from CNG production and use with electrical compression

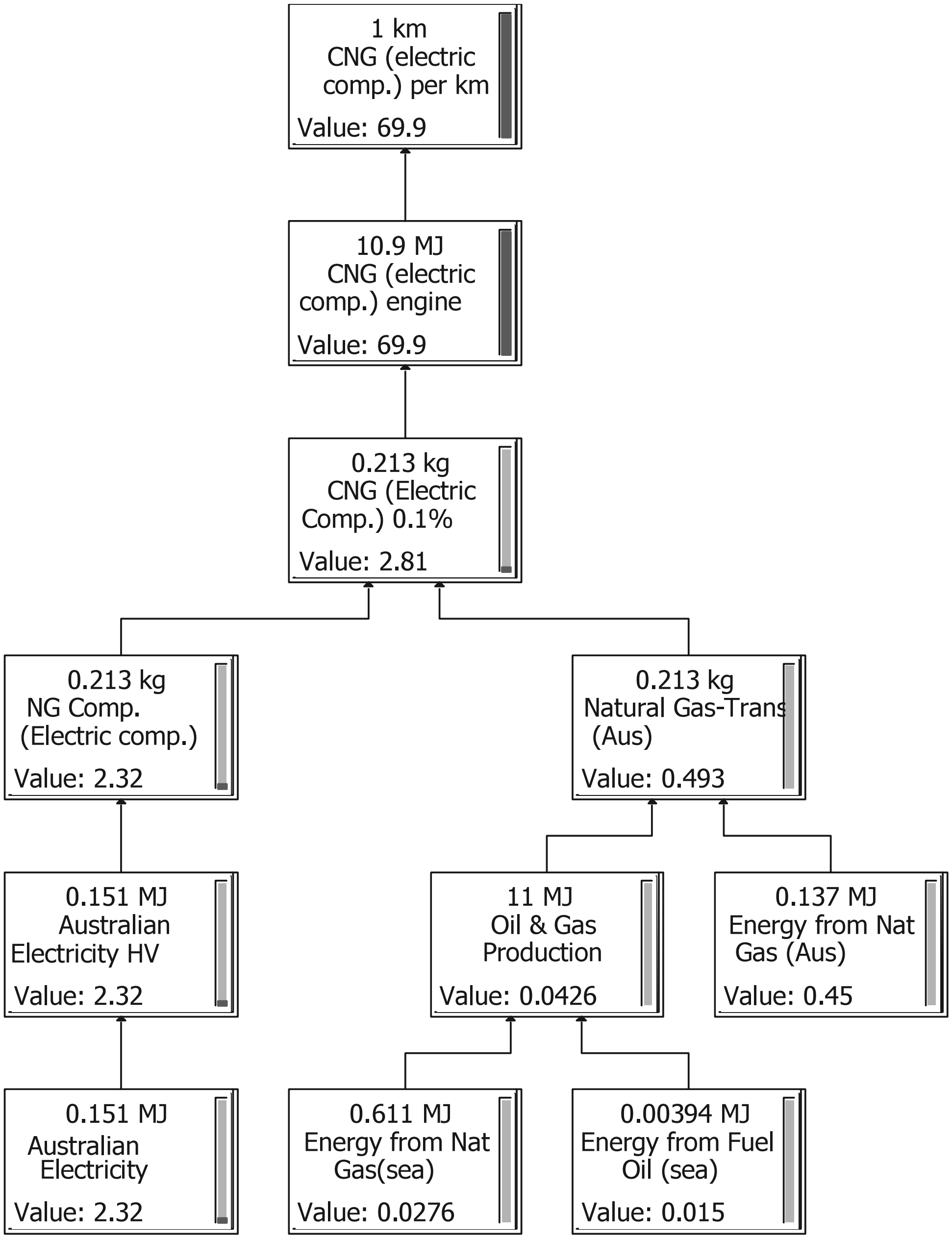

Figure 8.5
Exbodied particulate matter from CNG production and use with electrical compression

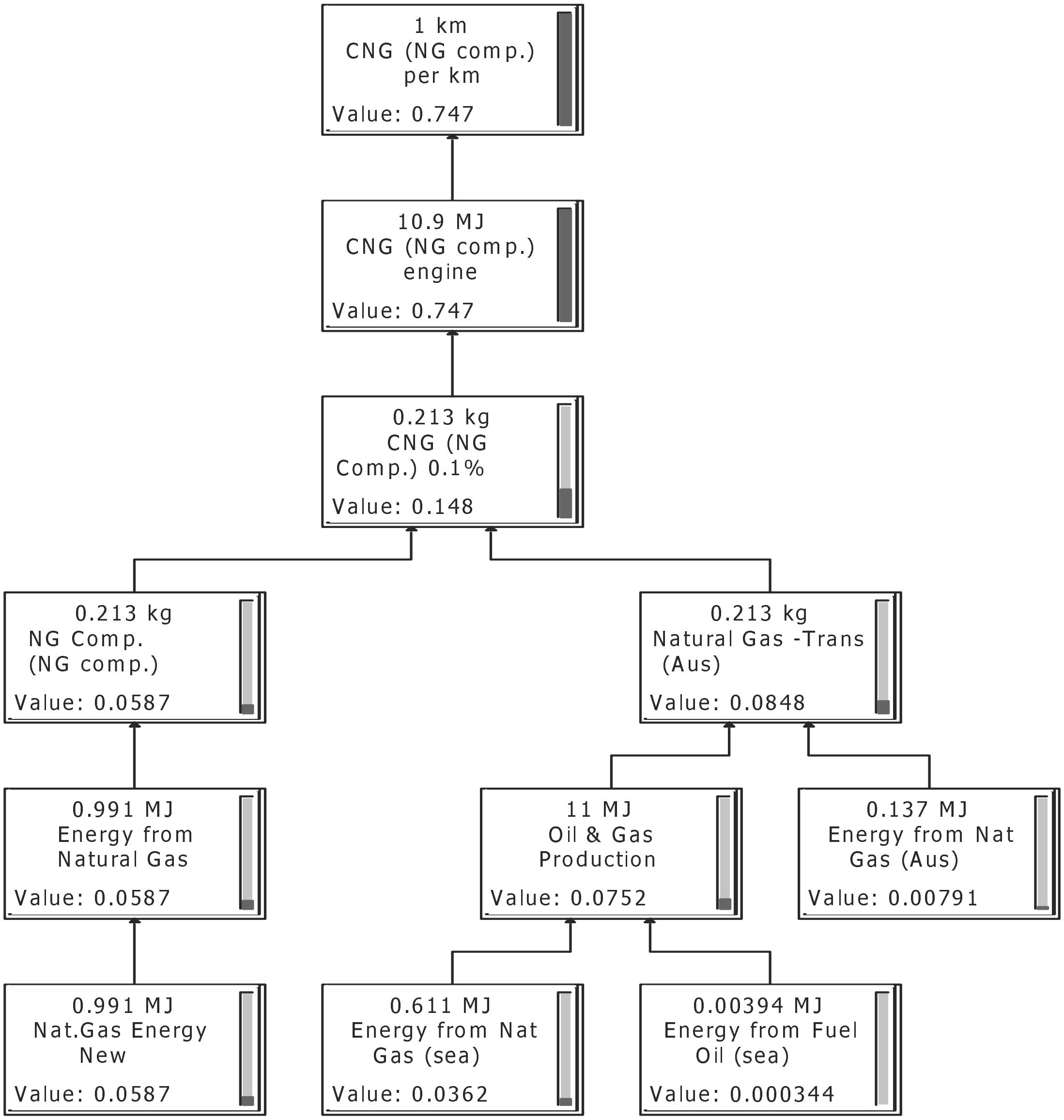

Figure 8.6
Exbodied greenhouse gases from CNG production and use with natural gas compression

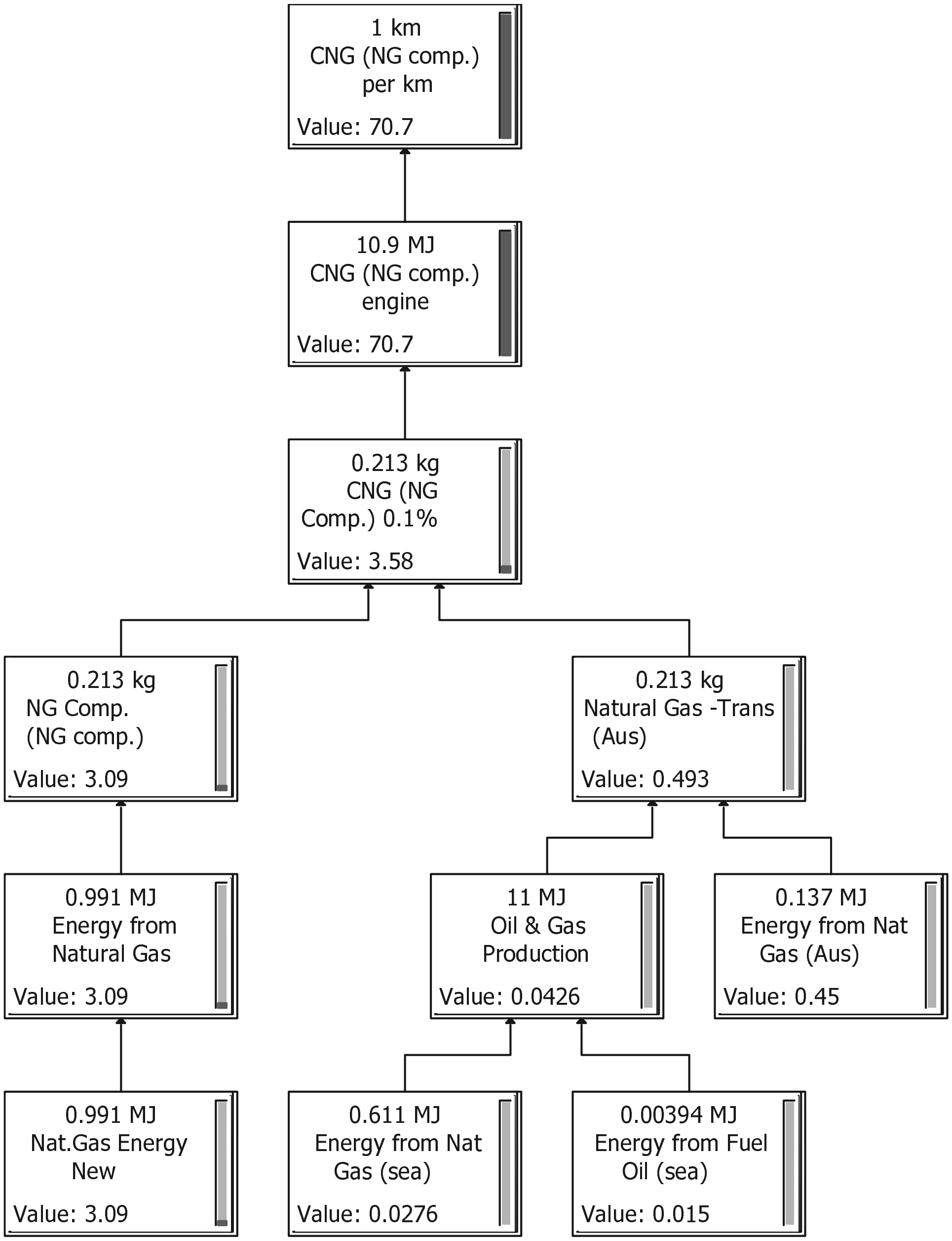

Figure 8.7
Exbodied particulate matter from CNG production and use with natural gas compression

8.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 8.20.

Table 8.20
Estimated one standard deviation uncertainties (in percent) for CNG emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	2	12
NMHC	135	135	135
NOx	50	29	72
CO	15	11	22
PM10	60	17	108

8.3.4 Discussion

Our results indicate lower greenhouse gas emissions both from tailpipe emissions and from upstream emissions. Earlier studies, such as those reported in the IPCC Second Assessment Report (Watson et al., 1996), the Expert Reference Group (1998) report, or those mentioned at http://www.hsph.harvard.edu/Organizations/hcra/diesel/diesel.pdf obtain different results. There are two reasons for this – changes in vehicle technologies, and the expected fugitive emissions.

Changes in vehicle technologies
The lower vehicle emissions arise from the improved performance of the present series of dedicated CNG engines that are optimised for the use of CNG. Earlier studies were based on a previous generation of CNG engines. This is evident when the history of the Western Australian experience is examined. The Expert Reference Group (1998) report examined issues associated with diesel and natural gas fuels and decided that diesel was the preferred fuel. The ANGVC (2000) responded with a review of the report and discussed what it believed to be the inadequacies of the report.

Following the Western Australian election, the decision to purchase diesel buses was reversed and natural gas buses were ordered. The firm Advanced Engine Components Ltd. was contracted to install its multipoint sequential electronic fuel injection natural gas vehicle system on Daimler-Chrysler M447G engines. The system was tested in June 2001 at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Zurich under the official European Transient Cycle. The engine was certified as being compliant with the Euro4 standard. The results of the tests done in June 2001, shown in Table 8.21, demonstrate that the present generation of NGV vehicles perform at Euro4 specifications.

Table 8.21
Emissions (g/kWh) from Daimler-Chrysler M447G engines

Technology	CO	THC	CH_4	NMHC	NOx	PM	CO_2	Specific Fuel Consumption
G20 Fuel Gas[2]	0.131	0.167	0.156	0.011	3.09	0.006	626	185-216
G25 Fuel Gas	0.134	0.479	0.459	0.02	2.88	0.007	637	185-216
Euro3 standard	5.45	2.38	1.6	0.78	5.0	0.16		
Euro4 standard	4.0	1.65	1.1	0.55	3.5	0.03		

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[2] EU reference fuel: G20 is 100% methane, G25 is 86% methane.

Fugitive emissions

The reduction in upstream emissions occurs because we assumed for Australia, on the basis of the advice received from stakeholders, that fugitive emissions are 0.1% of supply. This leads to the results, tabulated above, that exbodied emissions of greenhouse gases are less than that of diesel. Earlier studies and overseas studies, based on assumptions of higher fugitive emissions, produce opposite results in relation to greenhouse gases. We undertook a sensitivity study, as depicted in Figure 8.3, that indicates that if fugitive emissions exceed 4 % of supply then exbodied emissions of greenhouse gases exceed those of low sulfur diesel.

8.4 Viability and functionality

8.4.1 Safety

According to the IANGV web site (www.iangv.org/sources/ga.html) natural gas vehicles (NGV) have an excellent safety record (especially when compared to petrol driven vehicles). They cite two fundamental reasons for this: the structural integrity of the NGV fuel system and the physical qualities of natural gas as a fuel.

The fuel storage cylinders used in NGVs are much stronger than petrol tanks. The design of NGV cylinders are subjected to a number of specified “severe abuse” tests, such as heat and pressure extremes, gunfire, collisions and fires.

Though fuel storage cylinders are stronger than petrol tanks, when composite material used to encase the tanks, the materials are fundamentally more susceptible to physical damage than metals under abusive conditions. For this reason, composite materials on NGV cylinders must always be properly handled and protected. Incidents involving natural gas cylinder ruptures revealed that some form of chemical attack or physical damage to the composite overwrap on the cylinder was involved. This has been addressed in new cylinder standards by prescribing a standard acid exposure test.

NGV fuel systems are “sealed”, which prevent any spills or evaporative losses. Even if a leak were to occur in an NGV fuel system, the natural gas would dissipate into the atmosphere because it is lighter than air.

Natural gas has a high ignition temperature, about 650°C, compared with about 350°C for gasoline. It also has a narrow range of flammability; that is, in concentrations in air below about 5 percent and above about 15 percent by volume, natural gas will not burn. The high ignition temperature and limited flammability range make accidental ignition or combustion of natural gas unlikely.

8.4.2 Warranty

There are many dedicated natural gas vehicles available. These, are provided with standard manufacturers’ warranties. In the case of aftermarket conversions, third party warranties are also available to cover gas related components. As an example, the Cummins warranty for both ISC (Diesel) and C8.3G+ (Natural Gas) engines is identical.

8.4.3 Functionality

The knock resistance of methane is high, which is advantageous for engine performance. The Research Octane Number of methane is about 120, enabling compression ratios of up to 13:1 to be achieved in some OEM engines. Though the maximum efficiency of a spark-ignition gas engine is estimated to be 10-15% lower than the efficiency of a diesel engine (Nyland and

Lawson, 2000), the data that were used in our analysis (based on engine dynamometer information) indicate that CNG is only 1.5% less efficient than low sulfur diesel.

CNG buses appear to display a large discrepancy between their theoretical or engine dynamometer performance, and their on-road performance. According to Bates et al. (2001) in the current French NGV programme, natural gas buses have 28% to 62% worse fuel consumption than diesel buses under real-life driving conditions.

Examination of the literature in relation to the use of CNG as a fuel for bus fleets (Watt, 2000; SRI International, 1996; Los Angeles County Metropolitan Transportation Authority, 1999) reveals that in general, CNG buses require greater maintenance. Stage Coach New Zealand reports that fires have been caused by backfiring problems as a result of faulty maintenance, including a failure to re-install flash arresters. Bell Street Buses in Melbourne report similar problems (Watt, 2000). The ANGVC believes that current generation technology, if properly fitted and maintained, should not give rise to incidents such as these.

The Los Angeles Country Metropolitan Transportation Authority (LACMTA) notes that due to chronic problems with the engine and fuel system components, CNG buses have had a significantly greater defect rate than diesel buses. A fleet of Orion V CNG buses in operation in New York with NYCMTA consistently had twice the road failures as the same model of diesel bus. Engine and fuel system road calls for the CNG buses were also twice as high as the road calls for diesel engines and fuel systems. In Los Angeles, the LACMTA vehicles' engines and fuel system road calls accounted for approximately 48.5 percent of total road calls for the fleet, while engine and fuel system road calls for a fleet of older diesel buses only accounted for 34 percent of total road calls.

Until there is large-scale experience with CNG bus maintenance, reliability problems and the likelihood of faulty maintenance as a result of unfamiliarity with the equipment will be greater with CNG buses than with diesel buses. Fleet operators in Australia often report that a change in maintenance procedures results in improved reliability. Due to the small size and varying ages of CNG fleets in Australia, it is difficult to make an accurate statistical evaluation of vehicle reliability. Adjustments to maintenance procedures and adjustments to driving style may both result in improved reliability.

The performance of CNG engine and fuel system components are expected to improve as the technology matures. The performance of natural gas engine and fuel system components have improved considerably in recent years and are expected to improve further as the technology matures. In the past this has been hampered by low demand for natural gas engines but increasing demand for low emissions engines is likely to accelerate technology improvements and reduce price differentials between natural gas and diesel engines.

8.4.4 Operating range

We have noted that a typical range for a CNG truck is 560 km, which can be increased to over 640 km by increasing the number of cylinders on board the vehicle or by increasing the CNG pressure within the tanks at the time of fill. In the case of dual-fuel operations, diesel capacity may also allow for additional range.

CNG buses are heavier than the corresponding diesel vehicle as a result of the weight of the tanks. The Sydney Bus fleet menu on the web provides technical details on the Sydney Bus fleet at http://www.sydneybuses.nsw.gov.au/sb.fleet.html. According to the information provided there, a Scania L113CRB CNG bus has an unladen weight of 11,240 kg and can carry 72 passengers. The equivalent Scania L113CRL diesel bus has an unladen weight of 11,040 kg and can carry 69 passengers. These Scania CNG buses have a range of 250 km. The newer Sydney Bus CNG buses are Mercedes Benz 0405H buses with a range of 400 km. Developments in cylinder technology in recent years have increased the capacity for on board storage. Older model

Scania buses, for example, carried around 530 kg of cylinders (excluding mounting hardware) to deliver a driving range of only 250 km, whereas current Scanias can deliver over 450 kms with only 550 kg of cylinders (including mounting hardware) on board.

8.4.5 Re-fuelling

Sydney Buses describe their refuelling system as follows:

The refuelling station at State Transit Authority's Kingsgrove bus depot has two 500 m^3/hr compressors, eight 250 bar storage cylinders and the associated dispensers and reclaiming units. Each depot will have three compressors operating at a rate of 3000 cubic metres per hour at 34 MPa. The storage cascade has a total capacity of 3500 cubic metres. The buses will be able to be filled from empty to 20 MPa in three and a half minutes, with up to 40 buses being filled within two hours. The process is automatic with connection and disconnection of the coupling the only manual requirement.

Currently there are limited public CNG refuelling facilities (total 13) but over 30 public sites are expected to be operational by the end of 2002. In addition the demand for depot-based sites is increasing and it is expect that a similar number of additional depot based stations will be developed over this time. NGVs can also be fuelled from a small dispenser directly connected to a home or business natural gas line. This is commonly known as a Vehicle Refuelling Appliance (VRA). A small electrically driven compressor operates the dispenser.

8.4.6 Availability

Natural gas is abundant in Australia thus, in principle, there are no problems with fuel availability. In practice, natural gas is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplies to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. New pipelines are under construction to ensure alternate gas supply routes to Sydney and Melbourne.

8.5 CNG conversions

The majority of CNG vehicles in Australia were sourced as new vehicles. However, there has been growing interest in the conversion of conventionally fuelled vehicles to CNG through after-market conversions.

The emissions performance of converted Australian CNG vehicles is unclear due to a lack of comprehensive industry-wide data. The only results available were from one system that was used in a small number of vehicles. That system is currently being upgraded and is no longer sold in the previous configuration. Some tailpipe emissions from the previous configuration were much higher than those for OEM vehicles. It is possible that the difference in emission levels between converted vehicles and OEMs may decrease as the heavy-duty vehicles conversion industry becomes more firmly established.

8.6 Health Issues

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particles, smoke and odour. The effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined.

8.5.1 Production and transport

Particulate Matter

The LCA estimate for CNG urban precombustion (truck) PM10 emissions of 3 to 4 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air Toxics

The LCA estimate for CNG urban precombustion (truck) NMHC emissions of 0.007 to 0.011 g/km is substantially less than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

8.5.2 Use

Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost.

Exhaust emissions of methane, which is a greenhouse gas, are relatively high.

Particulate Matter

Research consistently shows that CNG (and gaseous fuels in general) with its simple chemistry and very low sulfur content, emit extremely low levels of particles. (Anyon, 1998)

Emissions of particulate matter are almost eliminated with natural gas use as shown in the earlier results tables. The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particle emissions.

The LCA estimate for CNG combustion (truck) PM10 emissions of 7.2 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

CNG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998)

CNG contains no benzene, so refuelling and running losses of this toxic would be zero. (USEPA, 1993)

The LCA estimate for CNG combustion (truck) NMHC emissions of 0.212 g/km is less than the LSD estimate of 0.900 g/km.

Summary

CNG upstream emissions of both particles and air toxics are substantially less than LSD. CNG tailpipe emissions of particles are substantially less than LSD. CNG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for CNG and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH);
- toluene; and
- xylene

8.7 OHS Issues

Australian long distance high pressure (up to 15 MPa) transmission pipelines are relatively modern (the oldest dates back to 1969) and built to high standards. They are well maintained and accidental leaks are a rarity. Refuelling CNG is considered to be the ‘least-safe’ moment of its use. CNG is much lighter than air and thus it is safer than spilled diesel. In the case of CNG leak, because of the gaseous nature of the fuel, the gas will issue as a very high velocity jet into surroundings aiding greatly in the rapid dispersion of the fuel.

The OHS issues in the lifecycle of CNG are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with CNG compared with LSD, no OHS issues unique to the production and distribution of CNG have been identified.

8.8 Vapour Pressure Issues

Most gas losses from the distribution systems are by way of leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters. It is estimated that emissions from the distribution network, called unaccounted gas, i.e. the difference between the gas issued by the utilities and the gas sold to customers are as high as 7.5% (NGGIC, 1996).

Since the use of CNG as a fuel requires a closed delivery system, evaporative emissions from a dedicated CNG vehicle are assumed to be zero. (USEPA, 1993). Different views are held on evaporative emissions. One is that CNG vehicles do not have any, due to their sealed pressurised fuel system. BTCE (1994), on the other hand, refers to ‘frequent leaks’ as a technical problem to be solved for NGVs.

8.9 Environmental Impact and Benefit

Noise levels from natural gas buses are less than those of diesel buses. Kadayifci and Bryett (1997) measured a decrease of 2 to 5 dBA during drive-by tests, and 2 to 3 dBA during stationary noise tests. Tests in France on identical diesel and CNG buses found up to 8 dBA reductions in noise outside the bus. Passengers experienced about 4dBA less noise (MVV InnoTec GmbH, 2000).

The operational experience is salutary. Perception problems about poor driveability of CNG buses were put to rest with comparison trials with diesel buses. The conclusion was that lack of noise from the CNG buses gave the drivers the impression of a lack of acceleration (Watt, 2000:p.66)

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particles, smoke and odour. The situation with regard to NO_x is less clear cut, and the effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined.

The potential for water and soil pollution is effectively eliminated by the use of natural gas.

With respect to sustainability, known world reserves of natural gas now constitute over 95% of equivalent oil reserves. In Australia this ratio is more than three times the oil reserve. Proven Australian resources of natural gas currently stand at 109,051 PJ, at existing production levels, this will last 91 years compared to domestic oil reserves which are estimated to last 39 years. Natural Gas is an indigenous fuel that, if broadly adopted by the transport industry, could result in the order of an additional 100PJ per annum of gas being consumed rather than imported and more expensive crude oil (ANGVC 2001).

CNG can also be a renewable fuel for vehicles because it can be purified from the biogas extracted from waste treatment facilities.

8.10 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 8.22 lists the estimated emissions factors for CNG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of CNG. The estimates of Arcoumanis (2000) indicate that CNG can be expected to meet all future Australian Design Rules for all pollutants.

Table 8.22
Estimated emission factors for CNG under future technologies (PM is unregulated)

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.3	**1.0**	0.9	**1.0**	0.2	**1.0**	0.1	1.0	0.9
Euro3	**0.53**	0.2	**0.6**	0.6	**0.71**	0.1	**0.67**	0.1	1.0	0.9
Euro4	**0.38**	0.1	**0.42**	0.4	**0.5**	0.1	**0.2**	0.05	1.0	0.8

8.11 Summary

8.11.1 Advantages

- CNG has very low particle emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.
- It contains non-toxic components.
- It is much lighter than air and thus it is safer than spilled diesel.
- Methane is not a volatile organic compound (VOC).
- Engines fuelled with natural gas in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.
- Natural gas is distributed via underground pipe networks, removing the need for hazardous transportation and transfer processes.
- Because of the pipeline delivery, retailers or fleet operators are not required to store large quantities of fuel, usually prepaid, on site.
- Natural gas use does not give rise to issues with groundwater contamination such as those experienced through diesel/petrol spillage or leakage from underwater storage.

- Natural gas pricing is stable and predictable, removing uncertainty to business caused by fuel price fluctuations.

8.11.2 Disadvantages

- CNG on board a vehicle takes 3 to 4.5 times more volume for storage than diesel, thus storage needs may be reduced.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- The composition may vary depending on the CNG source, which affects stoichiometric air/fuel ratios. This has not been a problem in Australia to date.
- It requires special refuelling stations that necessitate new infrastructure.
- The energy required to compress natural gas leads to increased greenhouse gas emissions.
- The extra weight of the fuel tank leads to higher fuel consumption or loss of payload.
- Exhaust emissions of methane, which is a greenhouse gas, are relatively high compared with low sulfur diesel.
- It can give rise to backfire in the inlet manifold if the ignition system is faulty or fails in use.
- Relatively small fugitive emissions of methane can have a significant effect on the exbodied greenhouse gas emissions.

9. Liquefied Natural Gas

9.1 Background

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH_4), and is produced either from gas wells or in conjunction with crude oil production. The composition of NG used in Melbourne in 1997/98 was 91.6% methane, 5.0% ethane, 0.4% propane, 0.1% butane, 0.8% nitrogen and oxygen, and 2.1% carbon dioxide. NG is consumed in the residential, commercial, industrial, and utility markets.

The interest in NG as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it must be stored on board a vehicle in either a compressed gaseous state (CNG) or in a liquefied state (LNG). In Australia, CNG is compressed to around 20 MPa for on-board storage. Methane liquefies at $-161^{o}C$. LNG is generally refrigerated to $-180^{o}C$ for liquefaction, and requires vacuum-insulated cryogenic tanks to maintain it in liquid form for storage.

9.1.1 Natural gas manufacture

NG consumed in Australia is domestically produced. Gas streams produced from reservoirs contain NG, liquids and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids. The separated gas is further processed to meet specified requirements. For example, NG for transmission companies must generally meet certain pipeline quality specifications with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen-sulfide content. A dehydration plant controls water content; a gas processing plant removes certain hydrocarbon components to hydrocarbon dewpoint specifications; and a gas sweetening plant removes hydrogen sulfide and other sulfur compounds (if present).

9.1.2 Natural gas market

The chapter on compressed NG includes a description of the pipeline system that is used to distribute NG throughout Australia.

LNG has long been used as a substitute for marine diesel fuel and is starting to be used as a heavy vehicle fuel. The low temperature facilities that are needed are expensive, and their manufacture, installation and operation increases the life-cycle emissions of greenhouse gases. The life-cycle emissions of LNG are likely to be comparable with those of CNG, as summarised above, except that the CO_2 emissions will be higher. The LNG market niche is centrally fuelled, heavy-duty fleet vehicles with high fuel consumption, where fuel cost savings can amortise equipment capital costs. LNG vehicle life-cycle costs will be lower than those for diesel vehicles when LNG equipment prices decrease and/or financial benefits such as emission reduction credit sales are realised. While there are no severe LNG vehicle technology problems, improvements are needed in areas such as accurate fuel level and flowrate instrumentation. The safety record is good, but it is difficult to quantitatively rate the LNG safety relative to gasoline and diesel vehicles because the statistical data needed does not yet exist. According to news reports at (http://www.lngexpress.com/japa.htm), Japan has a research program focussing on the use of

LNG in heavy-duty trucks and buses. Because Japan imports large quantities of LNG by sea, the cheapest fuel for a vehicle would be the imported LNG without any treatment. Japan therefore hopes to convert its diesel trucks and buses to LNG. The Australian situation is substantially different. Most NG is piped in gaseous form, not shipped. Centralised LNG facilities exist near Perth, Melbourne and Alice Springs. They are all relatively small scale. According to the Australasian Natural Gas Vehicle Council, recent developments also mean that smaller scale on-site liquefaction plants are likely to become more viable in Australia in the near future.

9.1.3 Fuel characteristics

NG has very different fuel characteristics from the fuels normally used in internal combustion engines. Louis (2001) cites a lower heating value of 52.9 MJ/kg. According to Perry's Chemical Engineering Handbook (5th edition, 1973: p. 9–13) the higher heating value of LNG, at –164°C is 23.9 MJ/L (when converted from imperial units). This corresponds to a lower heating value of 21.7 MJ/L, which is below that of automotive diesel (38.6 MJ/L). These two results indicate that LNG has a density of 0.41 kg/L. For comparison, as a gas its density, at 0.70 g/L, is lower than that of air.

9.1.4 Implications for engine conversions

According to a submission from Wesfarmers LNG:

"LNG as a heavy duty vehicle fuel is a recent development; improvements in vehicle tanks, storage vessels and dispensers have all contributed to its adoption by heavy vehicle fleets, and bus and locomotive operators. OEM manufacturers such as Cummins, Caterpillar and Detroit have greatly assisted by providing the heavy duty vehicle engines for NG. LNG gives these operators' vehicle range and refuelling times comparable to diesel without any power to weight disadvantages. Vacuum-insulated vehicle tanks are designed to replace the diesel units without any vehicle modifications. So, off-road down-time for truck/bus conversion is minimal.

It is estimated that there are 2,300 plus LNG vehicle globally, all currently in the northern hemisphere. An indication of the growth of this fuel is that a third vehicle tank manufacture is setting up to produce 1000 tanks per annum.

LNG will shortly be available from Wesfarmers Plant, North West Shelf Gas are to construct a domestic terminal supplying gas retailers from their existing facility and the possibility exists of LNG being available from the Victorian plant.

The first dedicated LNG truck is in Australia and will be shown to the industry at the Asia Pacific Natural Gas Vehicle Summit in Brisbane in April 2001."

9.2 Full Fuel-Cycle

9.2.1 Tailpipe

Collison et al. (1997) review the Maryland Mass Transit (MTA) pilot study of LNG buses using Cummins L10-240G NG engines. In this case the use of LNG, rather than CNG, arose because the heavy tanks needed to withstand CNG pressures meant that the extra weight (1,300 kg) put the buses close to their gross vehicle rating with just a modest passenger load. Using LNG resulted in a practical operating range. The MTA diesel buses averaged about 1.02 km/L and the

MTA LNG buses averaged about 1.02 km/L per diesel equivalent litre (based on the energy content of the fuels). Collison et al. (1997) claim that newer versions of the engines will improve fuel economy by using oxygen sensors and closed-loop computer controls during driving. However, idle fuel consumption consistently remains higher than that of diesel engines.

Table 9.1 shows the emissions obtained from the use of LNG buses. The measurements originally given in units of g/hp-h have been converted to g/kWh and g/MJ.

Table 9.1
Emissions from LNG buses using Cummins L-10 240G engines

	g/hp-h	g/kWh	g/MJ	LNG bus g/km	1998 Diesel bus g/km
NOx	2	2.68	0.74	5.1	10.7
PM	0.02	0.03	0.007	0.05	0.13
VOC	0.6	0.8	0.22	1.53	3.5

Source: (Collison et al. 1997)

In Table 9.2 we compare these to the emissions from the Cummins L-10 260G engines.

Table 9.2
Emissions from LNG buses using Cummins L-10 260G engines

	g/kWh
NOx	2.3
PM	0.03
NMHC	0.3
CO	0.5

Source: (Nylund and Lawson, 2000: Table 7.2))

Battelle (2000) provides a comprehensive evaluation of the Dallas Area Rapid Transit (DART) LNG bus site. These buses used the same Cummins L-10 G series of engines (Cummins L-10 280G in this case) even though Cummins discontinued the L-10G engine for NG operation in early 1999. Cummins continues to offer the C8.3G and B5.9G engines for transit and truck operation. Table 9.3 reproduces its data after conversion to metric units.

Table 9.3
DART LNG vehicles compared to diesel baseline vehicles (g/km)

Fuel	CO	NOx	THC	CH_4	NMHC[c]	PM	CO_2	km/L	MJ/km
LNG	0.146	13.28	8.56	7.81	0.03	a	1397	1.412[b]	25.49
Diesel	2.76	15.83	0.72		0.72	0.20	1640	1.641	22.20

a. Below limit of detection.

b. The fuel consumption mpg and km/L for the LNG are not the actual consumption figures. They are based on a miles per equivalent gallon using 137 cubic feet of NG at STP being equivalent to 1 gallon of ordinary (high sulfur) diesel.

c. The report claims that NMHC is calculated using THC-CH_4. The numbers in the report, reproduced in this table, do not obey this formula.

The Australasian Natural Gas Vehicle Council kindly provided emissions data from the latest generation of engines taken from various studies including UK test data on a CNG 113M engine using Mobil CNG (Andrew, 2001), data from Cummins on their 8.3 litre diesel and C8.3G engine with and without catalyst (Lyford-Pike, 2001) and data from a 9.8 L Transcom modified Renault 620-45 NG engine (AEC Limited), as well as data from South Australian CNG buses (ANGVC, 2001). The data in Table 9.4 was used in the quantitative analysis.

Table 9.4
Scania diesel and CNG test results (g/kWh) in the UK (Andrew, 2001)

	HC	CO	NOx	PM	CO_2
Diesel	0.864	1.442	7.014	0.373	756.3
CNG	0.212	0.018	0.962	0.007	674
LNG	0.18	0.017	1.532	0.013	698

Table 9.4 provides results of a test of the present generation of diesel engines (Scania DSC 11-21) as tested at the Millbrook Proving Ground in January 2001 (Andrew, 2001). The drive cycle was not specified. However, as the European Community requires Euro3 standards for heavy vehicles as from January 2000, we expect that both the engines and the test regime corresponded to Euro3. The specific fuel consumption during the test of the CNG vehicle was 190 g/kWh at 1100 to 1800 rpm. The minimum range of the CNG truck was 560 km. The truck achieved a range in excess of 640 km by increasing the CNG pressure from 200 bar to 250 bar.

9.2.2 Upstream emissions

Most LNG production facilities are located in north-western WA. At present all LNG produced is exported using purpose-built tankers. In case of the use of LNG in Australia as fuel for heavy vehicles, the production and delivery scenario of Figure 9.1 needs to be considered (IEA, 1997). There is no data on fugitive emissions of LNG trucked from the North West Shelf to appropriate distribution points, especially as vehicles powered by LNG will use LNG boil-off as part of their power source.

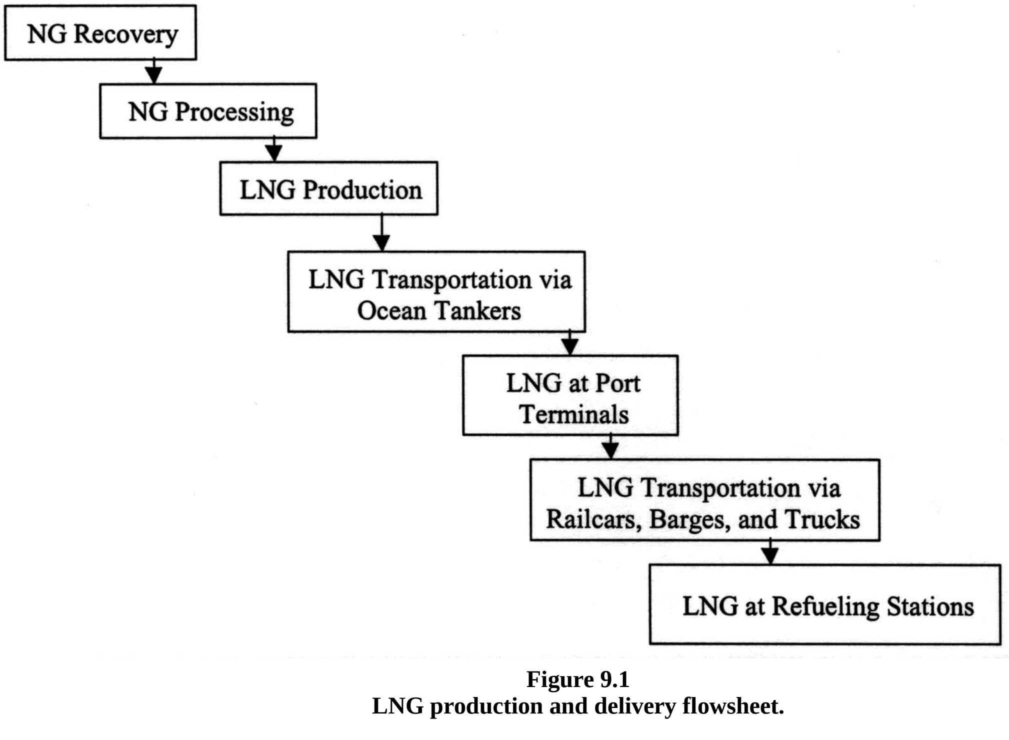


Figure 9.1
LNG production and delivery flowsheet.

The composition of the NG considered in this study is given in Table 9.5.

Table 9.5
Composition of the NG considered in this study

Component	Mol% (dry basis)
Methane (C1)	86.6
Ethane (C2)	5.8
Propane (C3)	3.1
Iso Butane (iC4)	0.8
Normal butane (nC4)	0.5
Pentane (C5)	0.5
Hexane plus (C6+)	0.1
Nitrogen (N_2)	0.4
Carbon dioxide (CO_2)	2.0
	100.0

Before liquefaction the gas is dried and the carbon dioxide removed. Carbon dioxide is removed using an amine wash system and exhausted into the atmosphere. Sulfur and all components likely to freeze during liquefaction (moisture, higher hydrocarbons) are also removed.

The liquefaction plant is modelled on the Air Products & Chemical multi-component refrigerant process with propane pre-cooling, which is the most common technology used in recent years. The refrigerant compressors consume the bulk of the power needed to operate the plant.

Transport calculations are based on a ship capacity of 75000 m^3. A full vapour return system is assumed to be operative at the loading jetty and the reception terminal. This means that any boil-off during loading and unloading operations is recovered.

Cargo boil-off during the sea voyage is used for powering ship’s utilities and for the vessel’s propulsion. Any shortfall of fuel is made up by fuel oil.

LNG can be delivered from port terminals to bulk terminals and refuelling stations via rail or road. Storage of LNG as cryogenic liquid in insulated storage vessels at pressures between 4 and 10 Bar is a standard practice. Any boil-off at storage facilities is recovered and used as fuel.

Data on liquefaction is taken from an International Energy Agency report on the existing state of the art facility in Sarawak (Malaysia) with corrections appropriate for the North West Shelf LNG facility. Inputs to LNG production are shown in Table 9.6

Table 9.6
Energy use in NG liquefaction

Fuel	Efficiency	Value in MJ	Comment
Energy from NG	94.6%	2686	90.5 MJ per 1000 MJ Gas (51.3 MJ/kg) compressed

Source : IEA Report No. PH2/12 “LNG Full Fuel Cycle: Emissions & Private Costs”, October 1997.

Production data for NG and emission data from energy from NG are shown in the CNG section.

For the shipping of LNG a total fuel use of 0.16 MJ per tonne.kilometre of gas transported is derived from the IEA data (Executive Committee of IEA Greenhouse Gas R&D Programme, 1997). Emissions are taken to be the same as those for NG usage in boilers, which is detailed in the CNG section.

9.2.3 Fugitive emissions

NG can contain significant quantities of naturally occurring CO_2, which in the past has often been vented to the atmosphere at the well-head. Le Cornu (1989) pointed to Cooper Basin gas as having up to 35 per cent by weight (12.7 per cent by volume) of naturally occurring CO_2. On a state-by-state basis, vented CO_2 accounts for between 3 and 15 per cent of full fuel-cycle CO_2 emissions from NG combustion (Wilkenfeld, 1991). Fugitive emission data used for NG production is described in the CNG section. A process tree for LNG production is shown in Figure 9.2 with the methane emission shown in grams as the lower value in each process box. The largest fugitive emission is in the assumed loss in fuel distribution, which is discussed in more detail below.

9.2.4 Methane emissions from vehicles

There is no data on fugitive emissions of LNG trucked from the North West Shelf to appropriate distribution plants, especially as vehicles powered by LNG will use LNG boil-off as their power source. Methane, the principal component of NG, has a greenhouse radiative forcing of 21 over a 100-year period. It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

Because methane is a non-reactive hydrocarbon, tailpipe emissions of methane are less well controlled by catalytic converters than the emissions of more reactive hydrocarbons (BTCE, 1994).

Experience with the LNG road train built to operate between Alice Springs and Yulara over a decade ago suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem. The LNG tanks, filled to 90 per cent of their volume, stood without use for 10 days before the pressure opened a relief valve. Stakeholders have suggested that today periods up to 14 days can easily be sustained.

9.2.5 Methane fugitive losses in distribution

Quantification of fugitive losses from methane distribution depends on the scenario adopted for transport and liquefaction of the LNG. On-site liquefaction and transport (via ship or truck) results in negligible fugitive losses. Pipeline distribution of the NG and subsequent liquefaction in urban liquefaction facilities will introduce much greater fugitive emissions. These emissions, emanating from high pressure distribution, will be lower than losses from low pressure urban gas distribution.

(Kadam 1999) has emission from gas processing plants at 0.1%, while the 1998 NGGI has total distribution losses for low pressure gas supply at 0.25%. In the final modelling, a figure of 0.1% has been used for fugitive emission of methane from LNG facilities – including all operations from the point of gas supply to the facility, up to, but not including, the combustion of the gas on board the vehicle (this is the same figure used for CNG distribution). A sensitivity analysis showing the effect of different levels of fugitive emissions is presented in Figure 9.3. It shows that up to 0.25% emission, the greenhouse gas emission results are still lower than the baseline diesel fuel, while at 10% the full fuel-cycle emission is substantially above the diesel baseline. The exbodied emissions and the baseline are the same at approximately 4% fugitive emissions.

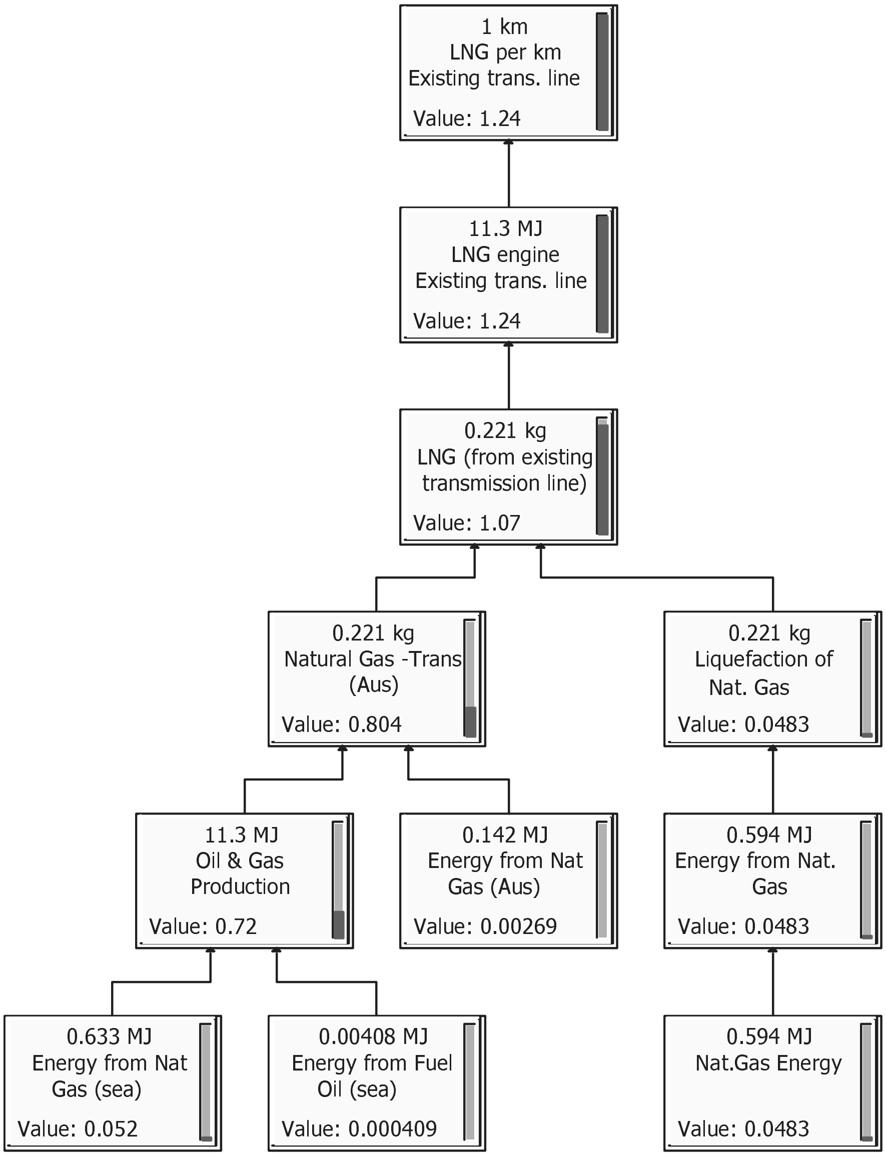
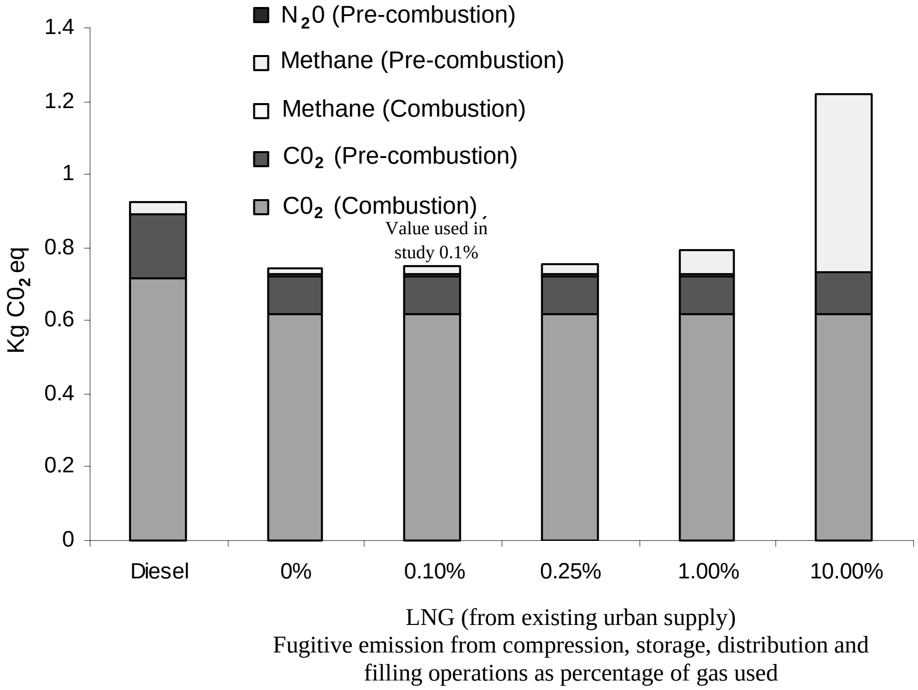


Figure 9.2
Methane emission in grams across LNG life cycle per km truck transport

Figure 9.3



Effect of different fugitive emission assumptions on full fuel-cycle greenhouse emission per km of truck travelled

We have estimated the fugitive emissions during bulk transfer and storage operations, on a g/MJ basis, as given in Table 9.7.

Table 9.7
Estimates (g/MJ) of fugitive CNG/LNG emissions during bulk transfer and storage

LNG losses at filling	Value	Comment
Spillage capacity on disconnect in mL	2.4	Parker Alternative Fuel Product Catalogue 3850
LNG density kg/m^3	420	See section 9.1.3
LNG lost per fill kg	0.001	per fill
g/km given 300 km between fills	0.0033	
g/MJ	0.000133	given fuel consumption in buses at 25 MJ/km
Diesel losses at filling		
Diesel g/l	0.006	from NGGIC workbook 2.1 1998
g/MJ	0.000167	given 36 MJ/litre for diesel
LNG loss as a percentage of diesel losses	80%	

9.2.6 Exbodied emissions

Modelling of the LNG scenarios for Australia is difficult in the absence of any substantial infrastructure operation for local transport. LNG production facilities are located in north-western WA which are used to produced export LNG. For LNG production in Australia three scenarios have been considered. The main scenario is based on production of LNG from urban gas supplies in Australian cities. This has been used as the baseline as there are facilities being built at Kwinana WA to supply local LNG. The other scenarios are based around use of the North West Shelf gas fields using ships to transport the LNG to east coast Australia, and road transport of LNG to Perth. The three scenarios are outlined in Figure 9.4.

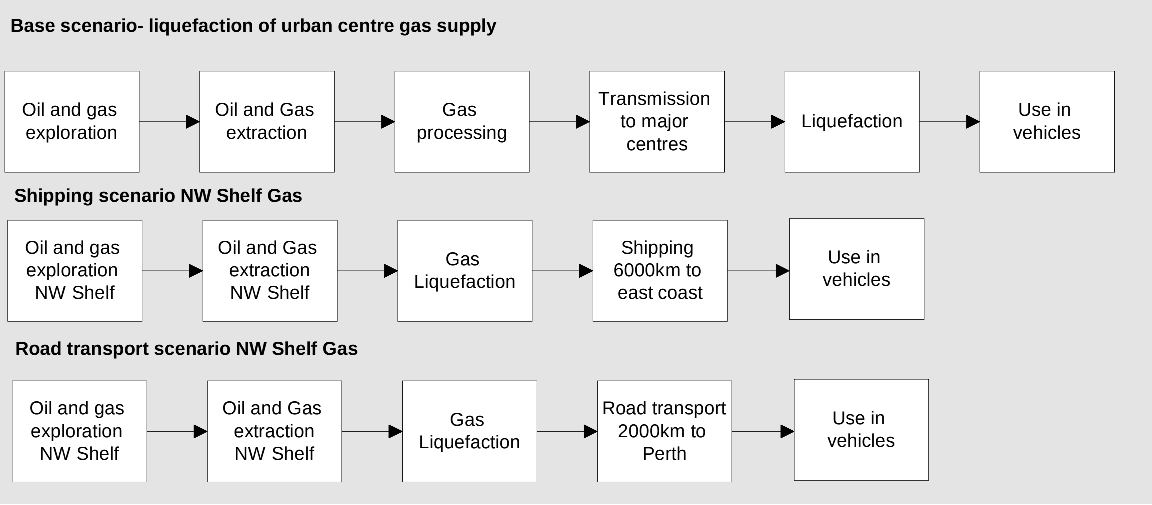


Figure 9.4
Different scenario for LNG production modelled in the study

The calculations in this section are the same as those for CNG, with an extra allowance for the emissions involved in liquefying the NG.

9.3 Results

Table 9.8
Urban and rural life cycle emissions calculated for diesel and LNG

Full life cycle	Units (per MJ)	LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.0858	0.0660	0.0666	0.0691
NMHC total	g HC	0.140	0.028	0.028	0.030
NMHC urban	g HC	0.111	0.002	0.002	0.003
NOx total	g NOx	1.044	0.204	0.206	0.242
NOx urban	g NOx	0.987	0.190	0.175	0.178
CO total	g CO	0.253	0.012	0.012	0.014
CO urban	g CO	0.242	0.006	0.003	0.004
PM10 total	mg PM10	40.7	0.5	0.5	2.3
PM10 urban	mg PM10	39.3	0.3	0.1	0.3
Energy Embodied	MJ LHV	1.18	1.11	1.11	1.14

Table 9.9
Urban and total precombustion emissions per MJ for diesel and LNG

Precombustion	Units	LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.0191	0.0113	0.0119	0.0144
NMHC total	g HC	0.0565	0.0262	0.0263	0.0284
NMHC urban	g HC	0.027	0.001	0.000	0.001
NOx total	g NOx	0.100	0.029	0.031	0.067
NOx urban	g NOx	0.043	0.015	0.000	0.003
CO total	g CO	0.023	0.009	0.009	0.011
CO urban	g CO	0.012	0.003	0.000	0.001
PM10 total	mg PM10	5.42	0.4	0.423	2.14
PM10 urban	mg PM10	4	0.208	0.00636	0.209
Energy Embodied	MJ LHV	1.18	1.11	1.11	1.14

Table 9.10
Urban and total combustion emissions per MJ for diesel and LNG

Combustion	Units	LS diesel	LNG
Greenhouse	kg CO_2	0.067	0.055
NMHC total	g HC	0.084	0.002
NMHC urban	g HC	0.084	0.002
NOx total	g NOx	0.944	0.175
NOx urban	g NOx	0.944	0.175
CO total	g CO	0.230	0.003
CO urban	g CO	0.230	0.003
PM10 total	mg PM10	35.26	0.12
PM10 urban	mg PM10	35.26	0.12
Energy Embodied	MJ LHV	0	0

Table 9.11
Summary of life cycle emissions from alternative fuels

		LS diesel	LNG	LNG NW shelf to East Coast	LNG NW shelf to Perth
Greenhouse	Precombustion	0.0191	0.0113	0.0119	0.0144
Greenhouse	Combustion	0.0667	0.0547	0.0547	0.0547
NMHC total	Precombustion	0.0565	0.0262	0.0263	0.0284
NMHC total	Combustion	0.0835	0.0016	0.0016	0.0016
NMHC urban	Precombustion	0.0271	0.0008	0.0001	0.0012
NMHC urban	Combustion	0.0835	0.0016	0.0016	0.0016
NOx total	Precombustion	0.1000	0.0293	0.0310	0.0668
NOx total	Combustion	0.944	0.175	0.175	0.175
NOx urban	Precombustion	0.043	0.015	0.000	0.003
NOx urban	Combustion	0.944	0.175	0.175	0.175
CO total	Precombustion	0.0225	0.0089	0.0093	0.0107
CO total	Combustion	0.2301	0.0031	0.0031	0.0031
CO urban	Precombustion	0.0123	0.0028	0.0001	0.0008
CO urban	Combustion	0.2301	0.0031	0.0031	0.0031
PM10 total	Precombustion	5.42	0.40	0.42	2.14
PM10 total	Combustion	35.26	0.12	0.12	0.12
PM10 urban	Precombustion	4.00	0.21	0.01	0.21
PM10 urban	Combustion	35.26	0.12	0.12	0.12
Energy Embodied	Precombustion	1.18	1.11	1.11	1.14

Units as in previous tables.

9.3.1 Emissions per unit distance

Table 9.12
Urban and total exbodied emissions per km for diesel and LNG

Full life cycle	**Units (per km)**	**LS diesel**	**LNG**	**LNG NW shelf to east coast**	**LNG NW shelf to Perth**
Greenhouse	kg CO_2	0.9250	0.748	0.755	0.784
NMHC total	g HC	1.509	0.315	0.316	0.340
NMHC urban	g HC	1.192	0.027	0.019	0.032
NOx total	g NOx	11.250	2.317	2.335	2.741
NOx urban	g NOx	10.638	2.153	1.989	2.017
CO total	g CO	2.723	0.136	0.140	0.156
CO urban	g CO	2.612	0.067	0.036	0.044
PM10 total	mg PM10	438.4	5.9	6.1	25.6
PM10 urban	mg PM10	423.1	3.7	1.4	3.7
Energy Embodied	MJ LHV	12.7	12.50	12.60	12.90

Table 9.13
Urban and total pre-combustion emissions per km for diesel and LNG

Precombustion	Units (per km)	LS diesel	LNG	LNG NW shelf to East Coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.2060	0.128	0.135	0.186
NMHC total	g HC	0.609	0.297	0.298	0.322
NMHC urban	g HC	0.292	0.009	0.001	0.014
NOx total	g NOx	1.080	0.333	0.351	0.757
NOx urban	g NOx	0.468	0.169	0.004	0.033
CO total	g CO	0.243	0.101	0.105	0.121
CO urban	g CO	0.132	0.032	0.001	0.010
PM10 total	mg PM10	58.4	4.53	4.8	24.3
PM10 urban	mg PM10	43.1	2.36	0.0721	2.36
Energy Embodied	MJ LHV	12.7	12.5	12.6	12.9

Table 9.14
Urban and total combustion emissions per km for diesel and LNG

Combustion	Units	LS diesel	LNG
Greenhouse	kg CO_2	0.719	0.620
NMHC total	g HC	0.900	0.018
NMHC urban	g HC	0.900	0.018
NOx total	g NOx	10.177	1.984
NOx urban	g NOx	10.177	1.984
CO total	g CO	2.480	0.035
CO urban	g CO	2.480	0.035
PM10 total	mg PM10	380.00	1.33
PM10 urban	mg PM10	380.00	1.33
Energy Embodied	MJ LHV	0	0

Table 9.15
Summary of life cycle emissions per km from diesel and LNG

		LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	Precombustion	0.2060	0.128	0.135	0.186
Greenhouse	Combustion	0.7190	0.6200	0.6200	0.6200
NMHC total	Precombustion	0.6090	0.2970	0.2980	0.3220
NMHC total	Combustion	0.9000	0.0180	0.0180	0.0180
NMHC urban	Precombustion	0.2920	0.0091	0.0008	0.0136
NMHC urban	Combustion	0.9000	0.0180	0.0180	0.0180
NOx total	Precombustion	1.0800	0.3330	0.3510	0.7570
NOx total	Combustion	10.170	1.984	1.984	1.984
NOx urban	Precombustion	0.468	0.169	0.004	0.033
NOx urban	Combustion	10.170	1.984	1.984	1.984
CO total	Precombustion	0.2430	0.1010	0.1050	0.1210
CO total	Combustion	2.4800	0.0348	0.0348	0.0348
CO urban	Precombustion	0.1320	0.0320	0.0008	0.0096
CO urban	Combustion	2.4800	0.0348	0.0348	0.0348
PM10 total	Precombustion	58.40	4.53	4.80	24.30
PM10 total	Combustion	380.00	1.33	1.33	1.33
PM10 urban	Precombustion	43.10	2.36	0.07	2.36
PM10 urban	Combustion	380.00	1.33	1.33	1.33
Energy Embodied	Precombustion	12.70	12.50	12.60	12.90

9.3.2 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results, as given in Table 9.16.

Table 9.16
Estimated one standard deviation uncertainties (in per cent) for low sulfur diesel emissions

	g/MJ	g/t-km	g/p-km
CO_2	5	6	8
NMHC	10	11	11
NOx	35	47	28
CO	60	18	106
PM10	45	48	46

9.4 Viability and Functionality

Kleenheat Gas informs us that one chassis-mounted HLNG-119 (410 L capacity) LNG tank is equivalent to seven CNG fibre-wrapped roof mounted tanks, so that there is more room available in an LNG vehicle than a CNG vehicle because the tanks occupy less space. LNG buses are about 400 kg heavier than equivalent diesel buses. A general rule is that a full LNG tank is 10% heavier than a full diesel tank for the same vehicle. They also point out that current LNG refuelling rates of 378 L per minute are common, and they consider this to be comparable to diesel refuelling rates.

Engines designed for CNG are used with LNG, by heating and vaporising the liquid fuel before it is fed to the engine. All commercially available LNG buses use engines that were originally designed for CNG, because the fuel enters the engine in a gaseous state. The liquid storage of the fuel is the only difference between CNG and LNG buses. This means that the emission characteristics, and most aspects of viability and functionality, will be the same for both CNG and LNG buses.

The Los Angeles Transit Authority (LACMTA) notes that LNG buses have the same reliability and operating cost issues as CNG buses. In addition, on-board cryogenic fuel pumps in the previous generation of LNG vehicles experienced short operating lives and high replacement costs. All modern LNG fuel systems are pump-less.

It is instructive to note the summary of the Dallas Area LNG Bus Fleet trials (Batelle, 2000), known as DART. The major conclusions from the evaluation of DART's LNG experience include the following:

- DART has had significant problems with startup of LNG operations, especially range. The buses were specified to have a 400 mile (640 km) range and were able to achieve only 277 miles (440 km) at the beginning of operation. A fourth LNG tank was added for on-board storage of LNG. This fourth tank provided enough fuel to make a range of 380 miles (600 km) which was deemed acceptable by DART. Several other problems with early failure of components in the engines (turbocharger, spark plugs, exhaust valve, cylinder head, and wastegate) fuel system (leaks), the fuelling station nozzle, and other systems have nearly all been resolved through a team effort at DART and with the vendors.

- The drivers report that the LNG buses are well matched in performance to diesel; it is difficult to tell them apart.
- The range problem caused reduced usage of the LNG buses at the start of operation. The range problem has been resolved by the fourth LNG tank. Today, the LNG buses are treated the same as the diesel buses in meeting the daily pullout requirements.
- The fuel economy has been steady at 1.62 miles per LNG gallon (0.685 km/L) or 2.70 miles per diesel equivalent gallon (1.14 km/L). DART along with ZF (the transmission vendor) and Cummins continue to explore ways to increase fuel economy with a goal of a 5–10% improvement.
- Some engine problems continue to be an issue for the DART LNG buses. Cummins continues to work on these problems even though the L10 engine has been discontinued as a commercial product. The resolution of problems with the L10 are applicable to the C8.3G, which is Cummins current heavy-duty NG engine for the transit market. Cummins is working on issues with spark plugs and wires, cylinder head design, turbo actuator, coils, and wastegate.
- Emissions testing from West Virginia University showed that the diesel engines at DART were very clean. The LNG emissions were cleaner. This emission testing at DART was a state-of-the-art comparison for transit with 1998 technology.
- Total operating costs for the LNG buses were only 3% higher than the diesel buses. However, the maintenance costs for the engine/fuel related systems were 33% higher for the LNG buses compared to the diesel buses. The fuel costs were 32% higher for the LNG buses compared to the diesel buses.
- Miles between roadcalls (on-road failure of an in-service bus) for the LNG and diesel buses overall were about the same. The LNG buses had 50 per cent lower miles between roadcalls for the engine/fuel rated systems compared to the engine/fuel related system roadcalls on the diesel buses.
- The LNG and NG vehicle (NGV) industry were challenged with making the DART operation a success due to the problems with range. The consortium of industry partners worked together and overcame the problems working through an “LNG Taskforce”. Today, all 139 LNG buses make pullout nearly every day.
- The two LNG fuelling station are working well for DART. Some problems have been experienced with fuelling nozzle leaks and driveaways with damage to the dispensing system. The nozzle has been redesigned and seems to be working better in managing leaks. DART is still exploring breakaway fitting and hose designs. The new LNG station at South Oak Cliff does not have the extensive length of piping (300 feet) from the storage tanks to the fuelling island that Northwest has. This has resulted in a much higher available fuelling rate, up to 70 gpm (265 L/min).

9.4.1 Safety

The safety regulations for all fuels - whether liquid or gaseous - will generally ensure that the risk of a fire under normal operating conditions is small. It is generally in the event of a crash or equipment failure that a hazard will occur. As with most fuels, the main fire hazard comes from leakage either during refuelling operations or during operation of the equipment, or a vehicle crash.

Three requirements must be met before there is a fire or an explosion. First, leakage of the fuel. Second, mixing of the fuel with air to give a mixture in the flammable range. Third, a source of ignition.

The likelihood of a flammable mixture occurring is less for NG than for LPG, since NG is lighter than air and rises. LPG vapour is heavier than air and tends to form ‘pools’ near the ground. It is generally accepted that the various automotive fuels range in safety from diesel (safest) to LPG as the most hazardous, with alcohol fuels, methane and petrol in the middle of the range.

9.4.2 Warranty

The Cummins base engine warranty on a C8.3G+ engine is 2 years, 250,000 miles (402,338 km), or 62590 hours of operation, whichever occurs first.

9.5 Health Issues

Emissions of particulate matter, some of which is carcinogenic, are almost eliminated with NG use (see Table 9.11). The IANGV (1990) noted that the NGV engine’s lubricating oil appeared to be the source of remaining particle emissions.

The life-cycle emissions of LNG are liable to be comparable with those of CNG, except that the CO_2 emissions will be higher. The major determinant of the life-cycle greenhouse gas emissions from the use of NG is the consideration of fugitive methane.

9.5.1 Production and transport

Particulate matter
The LCA estimate for LNG urban precombustion (truck) PM10 emissions of 2 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for LNG urban precombustion (truck) NMHC emissions of 0.009 g/km is substantially less than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. The disk accompanying this report provides details of air toxic emissions from upstream activities.

9.5.2 Use

NGVs have the potential to significantly reduce local air pollutants such as CO, NMHCs, SOx, particles, smoke and odour. The situation with regard to NOx is less clear cut although LNG has a lower adiabatic flame temperature than diesel, which implies lower NOx emissions. LNG has nearly zero sulfur levels and, thus, negligible sulfate emissions.

Particulate Matter

Research consistently shows that gaseous fuels in general, with their simple chemistry and very low sulfur content, emit extremely low levels of particles (Anyon, 1998).

Emissions of particulate matter, some of which is carcinogenic, are almost eliminated with NG use (see Table 2.10). The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particle emissions.

The LCA estimate for LNG combustion (truck) PM10 emissions of 1 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

CNG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998). It is reasonable to assume LNG would have similarly low toxics emissions.

As with CNG, LNG contains no benzene, so refuelling and running losses of this toxic would be zero. (US EPA, 1993).

The LCA estimate for LNG combustion (truck) NMHC emissions of 0.0180 g/km is less than the LSD estimate of 0.900 g/km.

9.5.3 Summary

LNG upstream emissions of both particles and air toxics are substantially less than LSD. LNG tailpipe emissions of particles are substantially less than LSD. LNG tailpipe emission of NMHC as well as benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for CNG and LSD has been identified for:
- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

9.6 OHS Issues

LNG is much lighter than air and thus it is safer than spilled diesel. Refuelling is considered to be the ‘least-safe’ moment of its use.

The OHS issues in the lifecycle of CNG are covered by a range of State and Commonwealth OHS provisions. While there will be different OHS issues involved in the production process associated with LNG compared with LSD, no OHS issues unique to the production and distribution of LNG have been identified.

9.7 Vapour Pressure Issues

Different views are held on evaporative emissions. One is that LNG vehicles do not have any, due to their sealed pressurised fuel system. BTCE (1994), on the other hand, refers to ‘frequent leaks’ as a technical problem to be solved for NGVs. Experience with the LNG road train built to operate between Alice Springs and Yulara suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem

9.8 Environmental Impact and Benefit

LNG is a gaseous fuel at normal temperature and pressure. It thus exhibits the same environmental benefits as CNG, namely lower greenhouse gas and air pollutant emissions than diesel, with no land or water pollution. Anecdotal evidence suggests that both drivers and passengers appreciate the lower noise levels of LNG vehicles, compared to diesel vehicles.

ESD principles

Noise levels from NG buses are less than those of diesel buses. LNG buses produce fewer air pollutants and greenhouse gases than diesel buses do. The potential for water and soil pollution is effectively eliminated by the use of NG.

Sustainability

NG is an indigenous fuel that could replace imported, expensive crude oil.

Groundwater

LNG is a gaseous fuel at normal temperature and pressure. Being a gaseous fuel, it does not impact groundwater.

9.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 9.17 lists the estimated emissions factors for CNG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of CNG. LNG can be expected to meet all future Australian design rules for all pollutants.

Table 9.17
Estimated emission factors for LNG under future technologies (PM is unregulated for gas engines)

Technology	**CO**	**CO**	**THC**	**THC**	**NOx**	**NOx**	**PM**	**PM**	**CO_2**	**LCA CO_2**
Euro2	**1.0**	0.3	**1.0**	0.9	**1.0**	0.2	**1.0**	0.1	1.0	0.9
Euro3	**0.53**	0.2	**0.6**	0.6	**0.71**	0.1	**0.67**	0.1	1.0	0.9
Euro4	**0.38**	0.1	**0.42**	0.4	**0.5**	0.1	**0.2**	0.05	1.0	0.8

9.10 Summary

9.10.1 Advantages

- LNG has very low particle emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.
- It contains non-toxic components. The liquefaction process removes impurities so that the LNG is pure methane, which is a non-toxic gas.
- It is much lighter than air and thus it is safer than spilled diesel.

- Methane is not a volatile organic compound (VOC).
- Engines fuelled with NG in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.
- NG pricing is stable and predictable, removing uncertainty to business caused by fuel price fluctuations.
- Where on site liquefaction is used, NG is distributed via underground pipe networks, removing the need for hazardous transportation and transfer processes.
- Where on site liquefaction is used, because of the pipeline delivery, retailers or fleet operators are not required to store large quantities of fuel, usually prepaid, on site.
- NG use does not give rise to issues with groundwater contamination such as those experienced through diesel/petrol spillage or leakage from underwater storage.

9.10.2 Disadvantages

- There is considerable extra infrastructure involved with gas liquefaction.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- Its driving range is limited because its energy content per volume is relatively low.
- It requires special refuelling stations and handling of a cryogenic liquid, making it suitable only for fleet operations.
- The energy required to liquefy NG leads to increased greenhouse gas emissions in comparison to CNG.
- Exhaust emissions of methane, a greenhouse gas, are relatively high compared with low sulfur diesel.
- Refuelling is considered to be the ‘least-safe’ moment of its use.
- It can give rise to backfire in the inlet manifold if the ignition system fails in use.

10. Liquefied Petroleum Gas — Autogas

10.1 Background

Liquefied petroleum gas (LPG) consists mainly of propane, propylene, butane, and butylene in various proportions according to its state or origin. The components of LPG are gases at normal temperatures and pressures, but can easily be liquefied for storage by an increase in pressure to about 8 atmospheres or by a reduction in temperature. In Australia, LPG used in motor cars is stored on board the vehicle in a steel cylinder in liquid form, but is converted to gaseous form via a regulator before supply to a gas-air mixer (the equivalent of a carburettor) for intake to the engine. There is very little usage of LPG in Australian heavy vehicles. Kleenheat Gas recently developed a diesel/LPG fuel substitution conversion kit that was used in a three month trial of an articulated Volvo B10M MkIII LPG bus in Darwin in late 2000 (see www.nt.gov.au/ministers/palmer/media00/1213lpgdiesel_darwinbus.shtml). Other manufacturers (Ecotrans, Was Diesel Now Gas) offer a similar capability. The few dedicated LPG engine options in Australia are designed to operate on the LPG-HD5 specification.

LPG is a by-product from two sources: natural gas processing and crude oil refining. Most of the LPG used in Australia is produced domestically, though a small quantity is imported. Natural gas, as extracted at the well-head, contains methane and other light hydrocarbons. The light hydrocarbons are separated in a gas processing plant using high pressures and low temperatures. In 1997, Australia produced 4.1 GL of LPG, of which 1.6 GL was from refineries.

The natural gas liquid components recovered during processing include ethane, propane, and butane, as well as heavier hydrocarbons. Propane and butane, along with other gases, are also produced during crude oil refining as a by-product of the processes that rearrange and/or break down molecular structures to obtain more desirable petroleum compounds.

More than 550,000 Australian vehicles use LPG. LPG powers all taxis in Victoria, and many other taxi fleets around the country. It is a familiar and widely available light vehicle fuel.

The utilisation of LPG as an automotive fuel varies very widely from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably petrol and diesel, Table 10.1 shows the variation in LPG fuel composition in Europe in 1982.

Table 10.1
LPG Composition (% by volume) as Automotive Fuel in Europe in 1982

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	-
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	-
Germany	90	10

Source www.vps.com/LPG/WVU-review.html

Table 1 indicates that there are two different classes of LPG. Autogas grade LPG is a mixture of propane and butane. A European specification (EN589) is presently being prepared to standardise the composition. In eastern Australia Anyon (1998) notes that the LPG mixture supplied is typically around 60-70% propane and 40-30% butane. The addition of butane slows down combustion speed in an engine, so that it reduces NOx emission, while it increases emissions of THC and CO.

In January 2000 the ALPGA published performance-based specifications for LPG. These are widely perceived to be more stringent than the European standards and have become a de-facto standard within Australia. The performance of passenger vehicles using different LPG grades has been documented by Watson and Gowdie (2000).

10.1.1 LPG in heavy vehicles

As a result of the recent environmental concern in relation to the health effects of particulate matter (Beer, 2000) and especially particulate matter of diameter less than 10 µm, known as PM10, LPG is being reconsidered as a heavy vehicle fuel. Particulate matter emitted by diesel is all PM10. Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost, though the LPG industry believes that a fully optimised LPG engine may be capable of producing lower particle emissions than an equivalent Euro4 diesel engine.

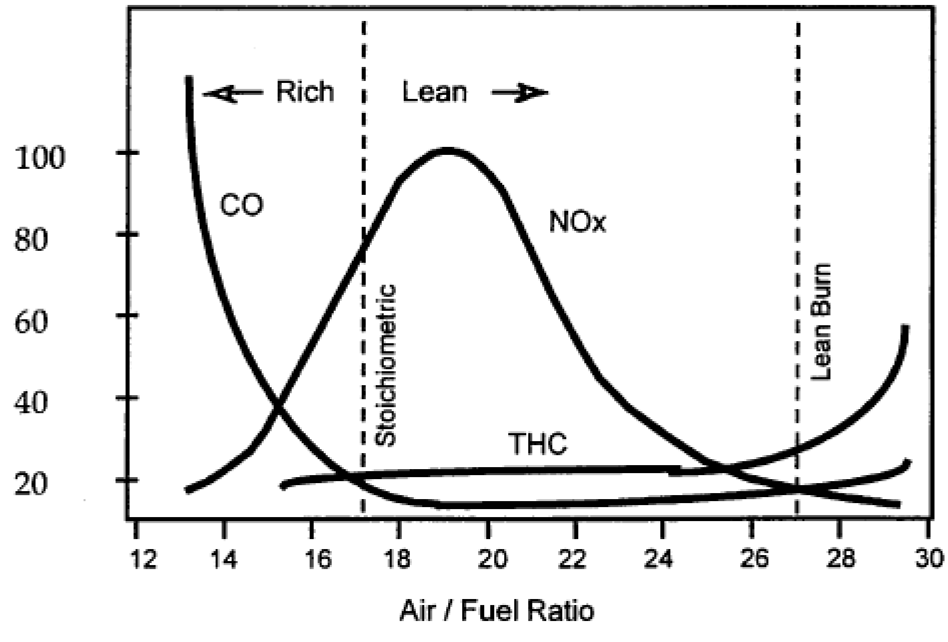


Figure 10.1
Influence of air-fuel ratio on emissions and fuel consumption of a spark-ignition engine.
The abscissa is a volume ratio, whereas the ordinate is in ppm (Nylund and Lawson, 2000).

DAF, the Dutch vehicle maker, has developed a dedicated LPG fuelled bus. DAF prefers the stoichiometric process over lean burn. The advantage of the stoichiometric combustion principle is that it allows the use of a three-way catalyst, which is impossible in lean burn. With a three-way catalyst the emission of all polluting compounds can be reduced, resulting in extremely low emission rates. If a two-way catalyst is used, the NO_x is not removed. The stoichiometric process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2. The drawback of the stoichiometric process is that it loses the efficiency advantage of lean burn and correspondingly increases CO_2 emissions. Figure 10.1 shows the influence of air-fuel ratios on emissions.

10.2 Exbodied Emissions

10.2.1 Emission tests

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics. There is considerable data in relation to LPG used in cars. (NSWEPA, 1997). In addition, most of the data that we were able to find relates to propane, rather than autogas. Beer et al. (2000) quote values provided by Anyon (1998), and the default values in the Australian NGGI. Nylund and Lawson (2000: Table 10.2) provide emission data for autogas for the DAF LPG 8.65 litre bus operating on a stoichiometric mixture and equipped with a three way catalyst. These are shown in Table 10.2., and were used in the subsequent full-fuel cycle analysis. According to publicity material about these buses the fuel consumption of these LPG buses varies between 0.5 and 0.9 L/km. (CADDET, 1997).

Table 10.2
Autograde LPG emissions

	CO (g/kWh)	**THC (g/kWh)**	**NOx (g/kWh)**	**PM (g/kWh)**	**FC (L/km)**
DAF GG170LPG	0.25	0.01	0.4	0.015	0.5-0.9
Diesel comparison	4	1.1	7	0.15	0.3-0.5

The properties of LPG, as given by NGGIC are given in Table 10.3.

Table 10.3
Properties of LPG (NGGIC, 1996, 1998)

Property	**Value**
Energy Density (HHV)	25.7 MJ/L
CO_2 Emission Factor	59.4 g/MJ
SO_2 Emission Factor	0.008 g/MJ

This chapter deals with dedicated LPG vehicles. Dual fuel LPG vehicles operating on LPG (autogas) are expected to have higher emissions than dedicated vehicles, given the results of dual fuel vehicles operating on LPG-HD5 referred to in the chapter on that fuel.

Table 10.4
Default Emission Factors (g/km) for LPG (NGGIC, 1996)

	Buses	Light Trucks	Medium Trucks	Heavy Trucks
CH_4	0.12	0.089	0.13	0.22
N_2O	0.011	0.008	0.011	0.02
CO	24.00	21.99	24.00	24.00
NMVOC	2.41	1.72	2.46	4.21
NOx	2.76	1.98	2.82	4.83

The default emission factors in the methodology for the Australian National Greenhouse Gas Inventory are given in Table 10.4.

10.2.2 Upstream

Raw natural gas from gas fields must be processed before being fed into pipelines or liquefied. Raw gas contains vapours and liquids, both hydrocarbons and water, which need to be separated.

In natural gas processing plants, non-hydrocarbon gases such as water, hydrogen sulfide (H_2S), and CO_2 are removed from the gas stream during a gas conditioning stage. Water is removed in a dehydrator through a chemical reaction with solvent or through physical adsorption.

The gas then passes through a processing stage where higher hydrocarbons are stripped from the gas. Stripping may be done by refrigeration (condensation, absorption in hydrocarbon solvent, adsorption on sorbents, compression, or any combination of the above methods. The particular configuration will depend on the composition of natural gas to be processed. Finally, stripped hydrocarbons are separated into ethane, LPG and pentanes plus.

Another source of LPG is crude oil processing at the refinery. LPG fraction is recovered from the top of the atmospheric pressure distillation unit and from various process units such as crackers and hydrotreaters.

Schematic diagram of LPG production and delivery is shown in Figure 10.2.

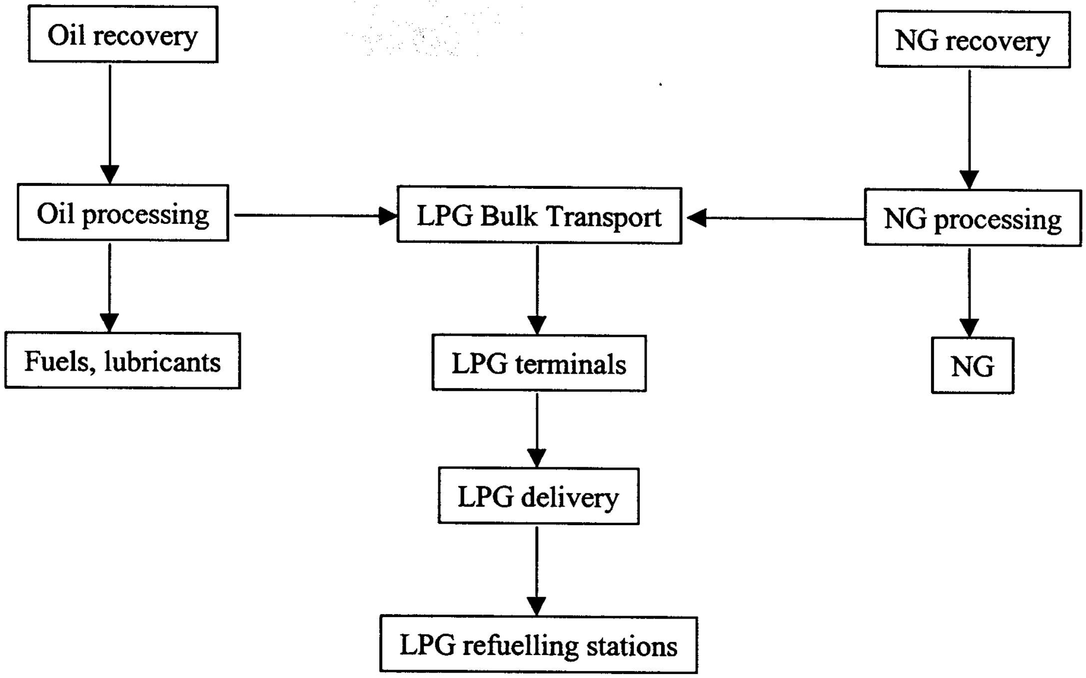


Figure. 10.2
LPG production and delivery flowchart.

Australian annual LPG production is about 6000 ML from combined natural sources and refinery production. Of this approximately 55% is used domestically and 45% exported. Bass Strait is the biggest source of LPG (over 40%), followed by Cooper Basin and the refineries.

Main Australian users are residential (cooking and heating), commercial/industrial (fuel), autogas (petrol/diesel replacement) and petrochemical (as feedstock).

While the term LPG means broadly a mixture of propane and butane, motor vehicles run on autogas which has to meet relevant specifications. Most important of those are the vapour pressure range required to be between 800 kPa and 1530 kPa at 40°C and minimum motor octane number of 92.

In some overseas countries automotive LPG (HD-5 specification) must contain a minimum of 95% propane, the balance being butane and propylene.

Upstream emissions associated with LPG use arise from energy used in gas and oil recovery and processing. Further emissions result from the delivery to retail outlets.

10.3 Results

Table 10.5
Urban and total life cycle emissions per MJ calculated for diesel and autogas

Full lifecycle	Units (per MJ)	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.0858	0.0764
HC total	g HC	0.140	0.102
HC urban	g HC	0.111	0.075
NOx total	g NOx	1.044	0.140
NOx urban	g NOx	0.987	0.089
CO total	g CO	0.253	0.038
CO urban	g CO	0.242	0.029
PM10 total	mg PM10	40.7	8.9
PM10 urban	mg PM10	39.3	7.6
Energy embodied	MJ LHV	1.18	1.06

Table 10.6
Urban and total precombustion emissions per MJ for diesel and autogas

Precombustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.0191	0.0170
HC total	g HC	0.0565	0.101
HC urban	g HC	0.027	0.074
NOx total	g NOx	0.100	0.092
NOx urban	g NOx	0.043	0.040
CO total	g CO	0.023	0.021
CO urban	g CO	0.012	0.012
PM10 total	mg PM10	5.42	5.31
PM10 urban	mg PM10	4	4.02
Energy embodied	MJ LHV	1.18	1.06

Table 10.7
Urban and total combustion emissions per MJ for diesel and autogas

Combustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.067	0.059
HC total	g HC	0.084	0.001
HC urban	g HC	0.084	0.001
NOx total	g NOx	0.944	0.048
NOx urban	g NOx	0.944	0.048
CO total	g CO	0.230	0.017
CO urban	g CO	0.230	0.017
PM10 total	mg PM10	35.26	3.55
PM10 urban	mg PM10	35.26	3.55
Energy embodied	MJ LHV	0	0

Table 10.8
Summary of life cycle emissions per MJ from diesel and autogas

		LS diesel	LPG (Autogas)
Greenhouse	Precombustion	0.0191	0.0170
Greenhouse	Combustion	0.0667	0.0594
HC total	Precombustion	0.0565	0.1010
HC total	Combustion	0.0835	0.0007
HC urban	Precombustion	0.0271	0.0742
HC urban	Combustion	0.0835	0.0007
NOx total	Precombustion	0.1000	0.0919
NOx total	Combustion	0.944	0.048
NOx urban	Precombustion	0.043	0.040
NOx urban	Combustion	0.944	0.048
CO total	Precombustion	0.0225	0.0208
CO total	Combustion	0.2301	0.0171
CO urban	Precombustion	0.0123	0.0116
CO urban	Combustion	0.2301	0.0171
PM10 total	Precombustion	5.42	5.31
PM10 total	Combustion	35.26	3.55
PM10 urban	Precombustion	4.00	4.02
PM10 urban	Combustion	35.26	3.55
Energy embodied	Precombustion	1.18	1.06

10.3.1 *Emissions per unit distance*

Table 10.9
Exbodied emissions per km for diesel and autogas

Full lifecycle	**Units (per km)**	**LS diesel**	**LPG (Autogas)**
Greenhouse	kg CO_2	0.9250	0.8352
HC total	g HC	1.509	1.108
HC urban	g HC	1.192	0.819
NOx total	g NOx	11.250	1.527
NOx urban	g NOx	10.638	0.969
CO total	g CO	2.723	0.415
CO urban	g CO	2.612	0.313
PM10 total	mg PM10	438.4	96.7
PM10 urban	mg PM10	423.1	82.6
Energy embodied	MJ LHV	12.7	11.6

Table 10.10
Precombustion emissions per km for diesel and autogas

Precombustion	**Units (per km)**	**LS diesel**	**LPG (Autogas)**
Greenhouse	kg CO_2	0.2060	0.1860
HC total	g HC	0.609	1.1
HC urban	g HC	0.292	0.811
NOx total	g NOx	1.080	1.000
NOx urban	g NOx	0.468	0.442
CO total	g CO	0.243	0.228
CO urban	g CO	0.132	0.126
PM10 total	mg PM10	58.4	58
PM10 urban	mg PM10	43.1	43.9
Energy embodied	MJ LHV	12.7	11.6

Table 10.11
Combustion emissions per km for diesel and autogas

Combustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.719	0.649
HC total	g HC	0.900	0.008
HC urban	g HC	0.900	0.008
NOx total	g NOx	10.177	0.527
NOx urban	g NOx	10.177	0.527
CO total	g CO	2.480	0.187
CO urban	g CO	2.480	0.187
PM10 total	mg PM10	380.00	38.75
PM10 urban	mg PM10	380.00	38.75
Energy embodied	MJ LHV	0	0

Table 10.12
Summary of life cycle emissions per km from diesel and autogas

		LS diesel	LPG (Autogas)
Greenhouse	Precombustion	0.2060	0.1860
Greenhouse	Combustion	0.7190	0.6492
HC total	Precombustion	0.6090	1.1000
HC total	Combustion	0.9000	0.0080
HC urban	Precombustion	0.2920	0.8110
HC urban	Combustion	0.9000	0.0080
NOx total	Precombustion	1.0800	1.0000
NOx total	Combustion	10.170	0.527
NOx urban	Precombustion	0.468	0.442
NOx urban	Combustion	10.170	0.527
CO total	Precombustion	0.2430	0.2280
CO total	Combustion	2.4800	0.1869
CO urban	Precombustion	0.1320	0.1260
CO urban	Combustion	2.4800	0.1869
PM10 total	Precombustion	58.40	58.00
PM10 total	Combustion	380.00	38.75
PM10 urban	Precombustion	43.10	43.90
PM10 urban	Combustion	380.00	38.75
Energy embodied	Precombustion	12.70	11.60

10.3.2 Uncertainties

In the absence of information on the variability and uncertainties associated with LPG emissions, we assume that the uncertainties are the same as those associated with LNG.

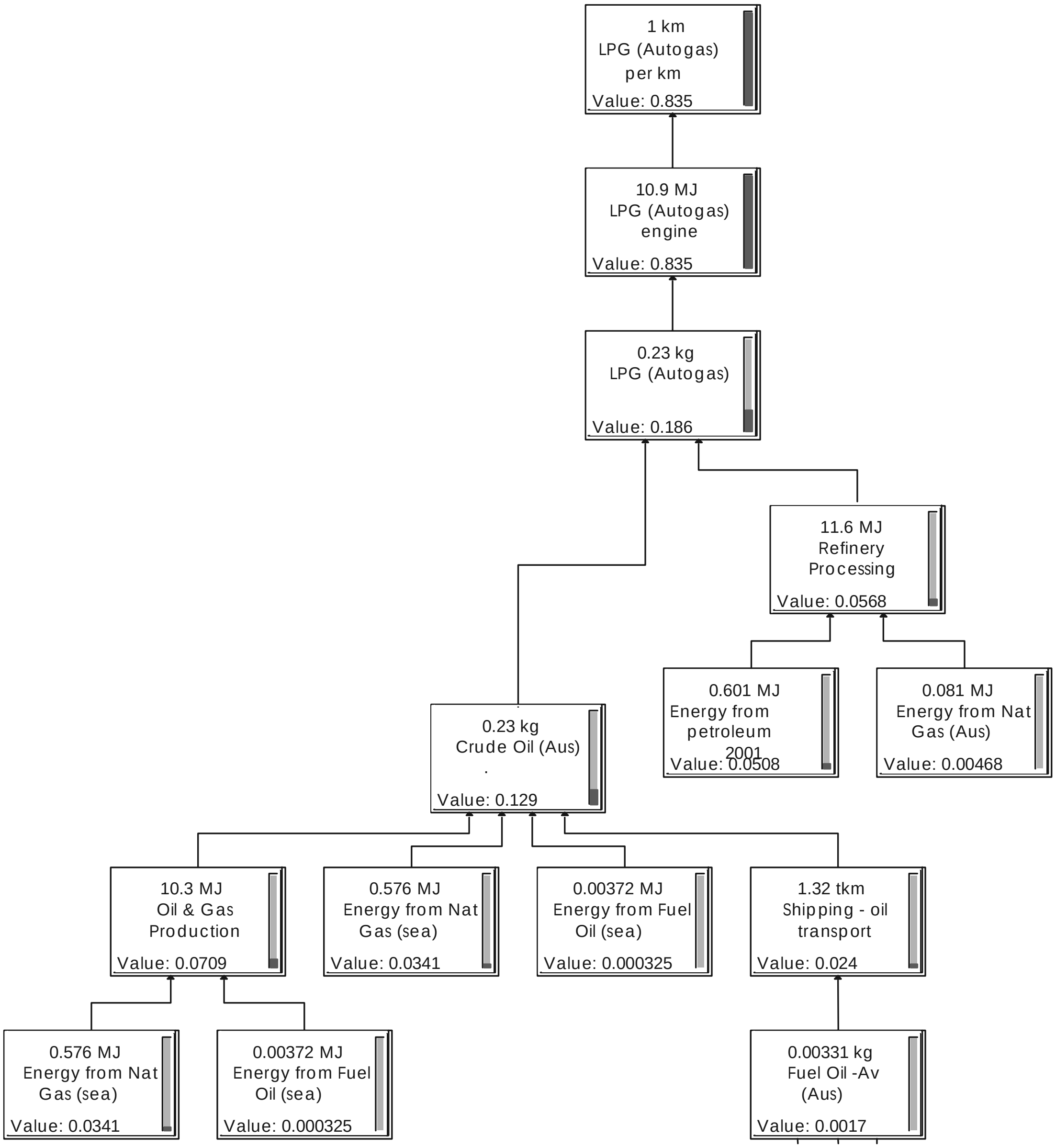


Figure 10.3
Exbodied greenhouse gases emissions (kg CO_2eq) from LPG (Autogas) production and processing and use in vehicle

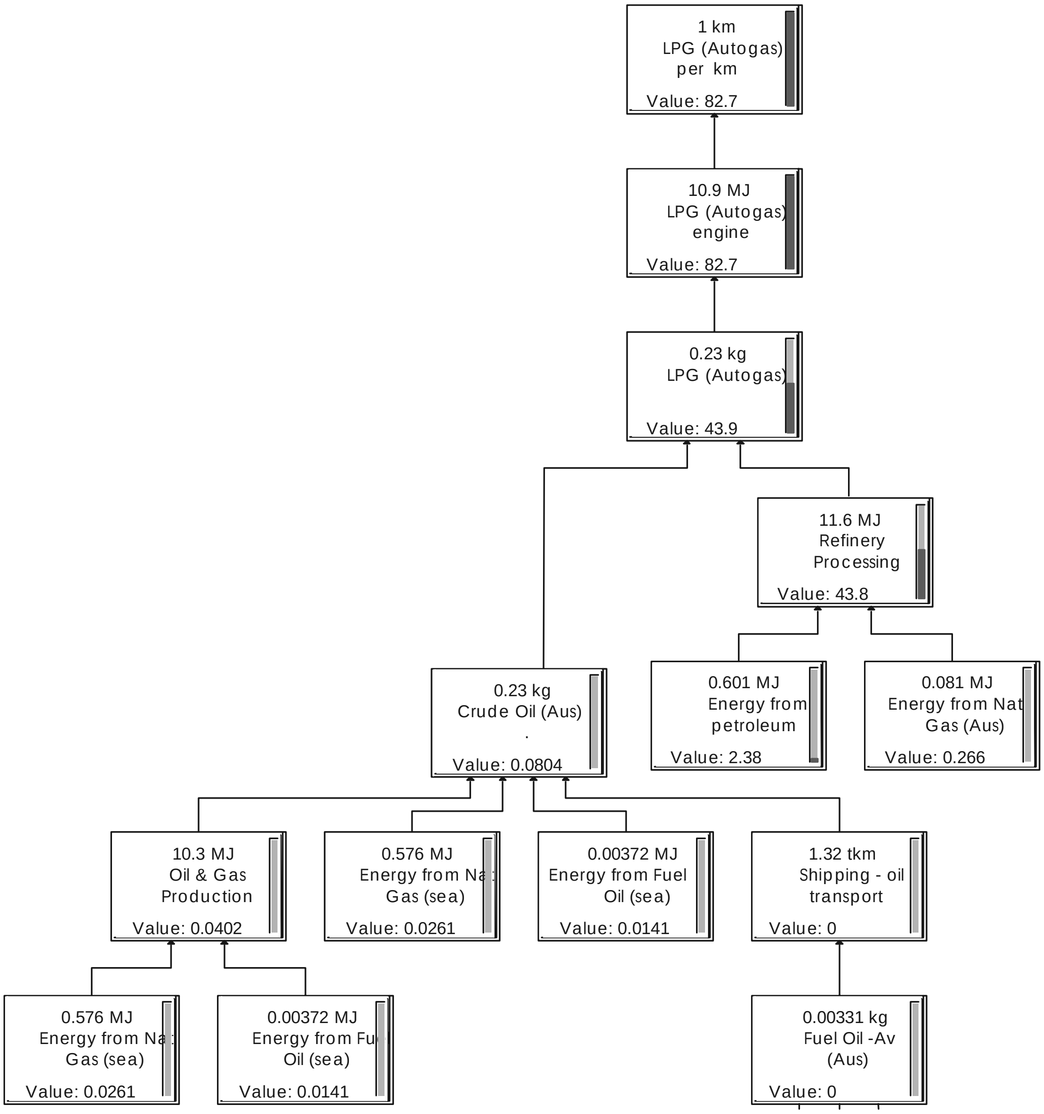


Figure 10.4
Exbodied particulate matter (mg - urban) from LPG (Autogas) production and processing and use in vehicle

10.4 Viability and Functionality

10.4.1 Handling, transport, storage and safety issues

LPG is gas at normal temperatures and pressures. Its physical properties depend strongly on the temperature and pressure at which it is being stored. As the temperature rises, the vapour pressure of LPG increases exponentially. Some ullage space must be left in an LPG tank because the liquid volume expands significantly if the tank encounters increasing ambient temperatures. Between –3^{o}C and 37^{o}C, for example, the liquid volume expands by 13 %. Due to this, and its lower density, LPG requires a 35 % greater storage volume than petrol. LPG systems have a safety device known as an automatic fill limiter (AFL) to ensure no more than 80 % of tank volume fills. This allows room for liquid expansion if the temperature rises after the tank is filled. Due to the low viscosity of LPG and its storage under pressure, it may leak through small cracks, pumps, seals and gaskets. LPG refuelling systems, being totally enclosed and pressure tight, have no refuelling, evaporative, running losses and emissions from the fuel storage system. LPG fuel tank is installed, along with a refuelling port, fuel lines, and pressure safety valves. LPG tanks are constructed of heavy gauge steel, to withstand a pressure of 1000 psi. Common operating pressures are in the range of 130-170 psi. Tanks are equipped with pressure relief valves that will release LPG vapours to the atmosphere to prevent tank explosion under abnormally high pressure conditions.

10.4.2 Engine manufacturers'acceptance of the fuel for warranty purposes;

Australian cars that are converted to LPG are warrantied by the converter. For example, Sprint Gas provides a 3 year, 100,000 km warranty on new cars (that have travelled less than 2,000km at the time of conversion) and a 2 year, 50,000 km warranty on used cars. (http://www.sprintgas.com.au/pgfive.html). Dedicated LPG cars typically have a 3 year, 100,000 km warranty provided by the manufacturer. Dedicated LPG heavy vehicles will come with similar warranties.

LPG engines are commercially available in the US from two major North American engine manufacturers for buses up to 30 feet in length. The Caterpillar G3306 and the Cummins B5.9-195 LPG engines were developed for mid-sized, heavy-duty vehicles. The Cummins B5.9-195 LPG engine is certified to the EPA 1999 Clean Fuel Fleet Vehicle Low Emission Vehicle (LEV) standard and the California Air Resources Board low NOx standard of 2.5 g/bhp-hr for heavy duty engines. Detroit Diesel discontinued development of an LPG version of the Series 50G and 60G for larger heavy duty vehicles.

In Europe, according to the web page of the Vienna bus fleet, the European manufacturer MAN will provide Vienna with extra LPG buses (http://www.klip.wien.at/english/verkehr/ve_bus.htm). Renault has developed an LPG bus, whereas DAF introduced the stoichiometric process for their LPG buses.

10.4.3 Functionality

Gaseous fuelled engines are generally considered easier to start than petrol or diesel engines in cold weather, because the fuel is vaporized before injection into the engine. Hot starting may, however, produce difficulties. After an engine is shut down, the engine coolant continues to absorb heat from the engine, raising its temperature. If the vehicle is re-started within a critical period after shutdown (when both the coolant and the engine are at high temperature) then the coolant will heat the gas more than normal, lowering its volumetric heating value and density.

10.4.4 *Fuel energy density and vehicle operational range;*

Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low. Thus LPG tanks take more space and weigh more than petrol or diesel fuel tanks. The range of LPG vehicles is equivalent to that of petrol or diesel vehicles.

10.4.5 *Refuelling requirements;*

The time to refuel LPG tanks is similar to that of refuelling times for petrol and diesel. The filling system of LPG tanks is not uniform across Europe, though new CEN standards are being designed to standardise this. In this respect, as with electricity plugs, Australia is ahead of Europe having standardised LPG refill nozzles across the country.

There are small losses of LPG during refuelling.

10.4.6 *Issues affecting the availability of fuel*

The 60% of Australian LPG that is sourced from natural gas is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplies to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. During the period of gas shortage, LPG was sourced from interstate and there were no disruptions to LPG supply. The NSW cavern storage provides added security.

10.4.7 *Other issues*

It is nowadays standard to use a multi-point fuel injection system. If this is not used then there can be back-firing to the inlet manifold. Some manufacturers discontinue fuel supply during deceleration to achieve the same result.

10.5 Health Issues

LPG’s low emissions have low greenhouse gas effects and low NOx precursors.

10.5.1 *Production and transport*

Upstream emissions associated with LPG use arise from energy used in gas and oil recovery and processing. Further emissions result from the delivery to retail outlets.

Particulate matter

The LCA estimate for LPG(Autogas) urban precombustion (truck) PM10 emissions of 44 mg/km is similar to the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for LPG(Autogas) urban precombustion (truck) HC emissions of 0.811 g/km is greater than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

10.5.2 *Use*

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics.

LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost. (Anyon 1998)

Anyon (1998) also points out that US tests on medium-large engines also confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 2.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km. Though these results may well refer to HD-5, it is likely that autogas would have similarly low emissions of air toxics.

Particulate matter

Research consistently shows that LPG (and gaseous fuels in general) with its simple chemistry and very low sulphur content, emit extremely low levels of particulate matter. (Anyon, 1998)

The LCA estimate for LPG(Autogas) combustion (truck) PM10 emissions of 39 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air toxics

LPG has very low 1,3 butadiene and benzene emissions, but aldehyde emissions increase substantially, as with alcohol fuels (compared to gasoline vehicles). However, these higher aldehyde emissions would likely be reduced with a catalyst specifically designed for an LPG vehicle. (USEPA, 1993). Compared to diesel vehicles LPG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde. (Anyon, 1998)

The LCA estimate for LPG(Autogas) combustion (truck) HC emissions of 0.008 g/km is substantially less than the LSD estimate of 0.900 g/km.

10.5.3 Summary

LPG upstream emissions of particulate matter are similar to LSD. LPG upstream emissions of air toxics are greater than LSD. LPG tailpipe emissions of particulate matter are substantially less than LSD. LPG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are expected to be less than LSD.

No comparative emissions data for LPG and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

10.5.4 OHS

The release of one unit volume of LPG in air generates a mixture that is around 2.5 times more than the volume of the mixture formed following the release of a similar amount of diesel.

The extent of hazards associated with such a leakage will depend largely on the relative tendency of the fuel to form a combustible mixture and the length of time for this mixture to persist in the vicinity of discharge and away from it either to be ignited from numerous potential ignition sources or feed a fire that may be engulfing the tank.

The tendency for the fuel to disperse in the surroundings from a leak is governed by the role of buoyancy and diffusional effects.

LPG vapour is heavier than air, disperses slowly, and can accumulate in local valleys. LPG, when involved in a leak will discharge in a liquid form requiring a period of time to vaporise and disperse. In the case of CNG leak, because of the gaseous nature of the fuel , the gas will issue as a very high velocity jet into surroundings aiding greatly in the rapid dispersion of the fuel.

It takes a minimum of from over 2 % by volume of LPG in air at ambient conditions to just support a continuous flame propagation, as compared to around 5 % for methane and 1 % for petrol. The ignition energy for LPG , as well as methane and petrol, are sufficiently low that ignition is usually assured in the presence of thermal ignition sources such as sparks, lighted matches, hot surfaces and open flames. The quenching of methane-air flames by cold surfaces, as indicated by quenching distance, is easier than in the case of flames involving LPG-air mixtures. Due to this, flame traps are more successful in suppressing methane fires than those involving LPG.

LPG fires tend to persist within the leakage area due to its liquid and heavier than air state. For fuel line ruptures, pressurised gaseous fuels represent higher hazard levels than petrol.

10.6 Environmental Issues

The environmental issues surrounding LPG are the same as those for CNG and LNG, in that they are gaseous fuels that do not cause land or water pollution.

LPG may be thought of as a natural gas by-product, or as a petroleum refinery by-product. In the former case the upstream environmental issues are those of CNG; whereas in the latter case the environmental issues are those of diesel.

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

10.7 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 10.13 lists the estimated emissions factors for LPG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of LPG. The estimates of Arcoumanis (2000) indicate that LPG can be expected to meet all future Australian Design Rules for all pollutants.

Table 10.13
Estimated emission factors for LPG under future technologies

Technology	**CO**	**CO**	**HC**	**HC**	**NOx**	**NOx**	**PM**	**PM**	**CO_2**	**LCA CO_2**
Euro2	**1.0**	0.4	**1.0**	0.5	**1.0**	0.3	**1.0**	0.3	**1.1**	1.2
Euro3	**0.53**	0.2	**0.6**	0.3	**0.71**	0.2	**0.67**	0.2	**1.0**	1.2
Euro4	**0.38**	0.1	**0.42**	0.1	**0.5**	0.2	**0.2**	0.05	**1.0**	1.1

10.8 Summary

10.8.1 Advantages

- It has low cold-start emissions due to its gaseous state.
- It has lower peak pressure during combustion, which generally reduces noise and improves durability; noise levels can be less than 50% of equivalent diesel engines.
- LPG fuel systems are sealed and evaporative losses are negligible.
- It is easily transportable and offers 'stand-alone' storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- It contains negligible toxic components.
- LPG has lower particle emissions and lower noise levels relative to diesel, making it more attractive for urban areas.
- Its low emissions have low greenhouse gas effects and low NOx precursors.
- Relative to other fuels, any increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

10.8.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is lower than diesel, which explains why LPG tanks take more space than diesel fuel tanks. They are pressure vessels so that they also weigh more than diesel tanks.
- It is heavier than air, which requires appropriate handling.
- Though the lower flammability limit for LPG is actually higher than the lower flammability limit for petrol, the vapour flammability limits in air are wider than those of petrol, which makes LPG ignite more easily,
- It has a high expansion coefficient so that tanks can only be filled to 80% of capacity.
- LPG in liquid form can cause cold burns to the skin in case of inappropriate use.

11. Liquefied Petroleum Gas — HD5

11.1 Background

HD5 requires a minimum propane (C_3H_8) content of 90% and a propylene content of less than 5% on a volume basis. The remainder is normally n-butane (C_4H_{10}), with isobutane and butanes also present. LPG HD-5 is essentially propane. Table 11.1 gives properties of liquefied petroleum gas (LPG) HD5 based on its main component, propane.

Table 11.1
Properties of LPG HD5 (Propane)

Property	Value
Liquid density	499 kg/m^3
Energy density (LHV)	23.1 MJ/L
CO_2 emission factor	65 g/MJ

The components of LPG are gases at normal temperatures and pressures, but can easily be liquefied for storage by an increase in pressure to about 8 atmospheres or by a reduction in temperature. In Australia, LPG used in motor cars is stored on board the vehicle in a steel cylinder in liquid form, but is converted to gaseous form via a regulator before supply to a gas-air mixer (the equivalent of a carburettor) for intake to the engine. There is very little usage of LPG in Australian heavy vehicles, though the company Was Diesel Now Gas undertakes conversions of vehicles to run on HD-5. The few dedicated LPG engine options in Australia are designed to operate on LPG-HD5.

LPG is a by-product from two sources: natural gas processing and crude oil refining. Most of the LPG used in Australia is produced domestically, though a small quantity is imported. Natural gas, as extracted at the well-head, contains methane and other light hydrocarbons. The light hydrocarbons are separated in a gas processing plant using high pressures and low temperatures.

The natural gas liquid components recovered during processing include ethane, propane, and butane, as well as heavier hydrocarbons.

Propane and butane, along with other gases, are also produced during crude oil refining as a by-product of the processes that rearrange and/or break down molecular structures to obtain more desirable petroleum compounds.

The utilisation of LPG as an automotive fuel varies very widely within a country and from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably gasoline and diesel. Table 11.2 shows the variation in LPG fuel composition in Europe in 1982. The performance of passenger vehicles using different LPG grades has been documented by Watson and Gowdie (2000).

Table 11.2
LPG Composition (% by volume) as automotive fuel in Europe in 1982

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	-
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	-
Germany	90	10

Source: www.vps.com/LPG/WVU-review.html

Table 11.2 indicates that there are two different classes of LPG. LPG HD5 is used in the United States. Its specifications have been regulated by the California Air Resources Board (http://www.arb.ca.gov/regact/lpgspecs/lpgspecs.htm) under Amendment of Title 13, California Code of Regulations, section 2292.6.

In 1992, the Board adopted section 2292.6, which took effect on January 1, 1993. The Board included a maximum limit of 10% by volume on the propylene content of vehicular LPG. That propylene limit was to have declined to 5% on January 1, 1995. However, in 1994, the Board delayed the effective date of the 5% propylene limit to January 1, 1997, and then in 1997, the Board again delayed the effective date of the propylene limit until January 1, 1999. In the interim, the propylene limit remained at 10% by volume. The Board delayed the effective date of the propylene limit out of concerns raised by the vendors of commercial propane (who supply the motor vehicle LPG used in California) that too little of the commercial propane available to them meets the original specifications set by the Board.

The LPG specifications also include a maximum limit on butanes and heavier species, of 2.5% by volume. This limit is also contained in the specifications for industrial and commercial grade propane.

When the Board adopted the specifications for vehicular LPG, and other alternative fuels, it set essentially identical standards for the motor vehicle fuel sold commercially in California and the fuel used for emission standard certification testing of new motor vehicles. The purpose for the commercial fuel specifications is to ensure that motor vehicles certified on LPG will receive in-use fuel having a quality similar to that of the certification fuel, so that the vehicles will achieve their emission standards in use.

On 8 December 1999 the following amendments came into force:

(1) Retain the current interim propylene limit of 10% by volume as a permanent limit.

(2) Establish a new 2.0% by volume maximum limit for butenes.

(3) Establish a new 0.5% by volume maximum limit for pentenes and heavier.

(4) Amend the optional 2.5% by volume maximum limit for butanes and heavier to a 5.0% by volume limit for butanes.

(5) Reduce the maximum sulfur content limit from 120 to 80 parts per million by weight.

Finally, the Board approved an amendment, which requires the staff to review the LPG regulation in five years to determine whether it should be retained, revised, or repealed.

11.1.1 LPG in heavy vehicles

As a result of the recent environmental concern in relation to the health effects of particulate matter (Beer, 2000), especially particulate matter of diameter less than 10 μm known as PM10, LPG is being reconsidered as a heavy vehicle fuel. Particulate matter emitted by diesel is all PM10. Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost, though the LPG industry believes that a fully optimised LPG engine may be capable of producing lower particulate emissions than an equivalent Euro4 diesel engine.

DAF, the Dutch vehicle maker, has developed a dedicated LPG fuelled bus. DAF prefers the stoichiometric process over lean burn. The advantage of the stoichiometric combustion principle is that it allows the use of a three-way catalyst, which is impossible in lean burn. With a three-way catalyst the emission of all polluting compounds can be reduced, resulting in extremely low emission rates. If a two-way catalyst is used, the NO_x is not removed. The stoichiometric process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2. The drawback of the stoichiometric process is that it loses the efficiency advantage of lean burn and correspondingly increases CO_2 emissions. Figure 1.1 shows the influence of air-fuel ratio on emissions.

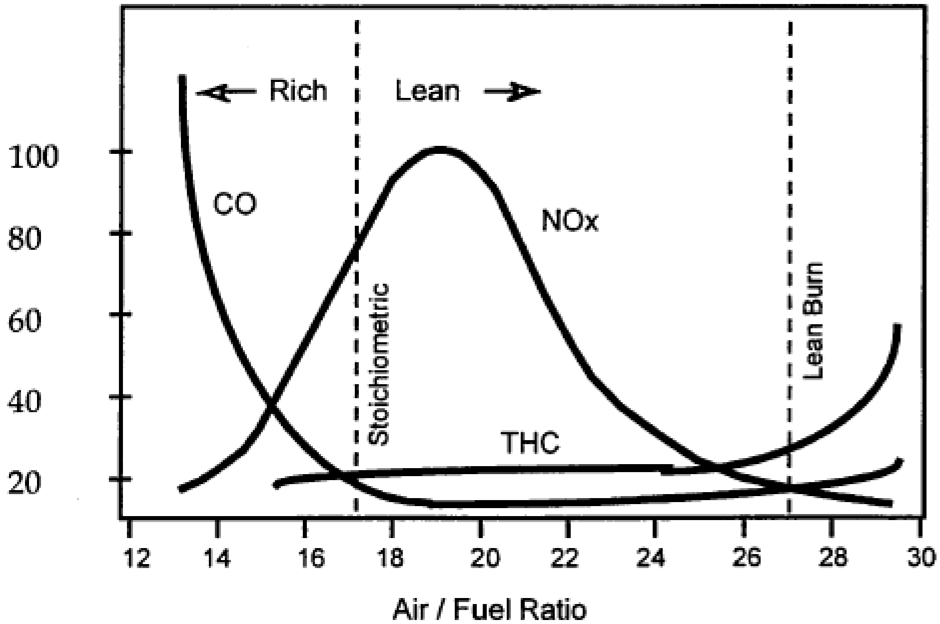


Figure 11.1
Influence of air-fuel ratio on emissions and fuel consumption of a spark-ignition engine. The ordinate is in ppm, and the abscissa is a volumetric ratio (Nylund and Lawson, 2000).

11.2 Exbodied Emissions

11.2.1 Emissions tests

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics. There is considerable data in relation to LPG used in cars. (NSWEPA, 1997).

Beer et al. (2000) quote values provided by Anyon (1998) reproduced in Table 11.3. As a result of stakeholder input, and a further literature search we found further information as given in Table 11.4. The Cummins B5.9LPG data from ADEPT (1998) was used in our analysis.

The LPG sold in the United Kingdom, Ireland, Sweden, Germany and in the United States (when sold as HD5) is propane. As noted by ANGVC (2000) this means that the widely quoted Millbrook trials data, Table 11.3, for the LPG bus in the London Transport Study (Anyon, 1998; Expert Reference Group, 1998; Beer et al., 2000) refers to propane rather than the LPG sold in eastern Australia.

Table 11.3
LPG (Propane) emissions (g/km)

	CO	**THC**	**NOx**	**PM**	**CO_2**
London LPG Bus with 3 way catalyst	0.13	0.03	5.4	0.02	1309

Table 11.4
LPG (Propane) emissions (g/kWh)

	CO	**THC**	**NMHC**	**NOx**	**PM**	**CO_2**	**FC**
Ford 6.8L V10 engine (Nylund & Lawson, 2000:p105)	3.8		0.15	0.7			
Cummins B5.9LPG with catalyst (ANGVC submission)	1.34		1.09*	3.06*	0.01		
Cummins B5.9LPG (ADEPT, 1998)	0.56	1.185	1.138	3.724	0.008	897.8	315

*These values were from T. Green of Cummins Inc.

Anyon (1998) also points out that US tests on medium-large engines confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 11.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km.

The default emission factors in the methodology for the US Greenhouse Gas Inventory are given in Table 11.5 in terms of pounds per million BTU (the original units), and their conversion into g/MJ, for both controlled (i.e. equipped with catalytic converters) and uncontrolled vehicles.

Table 11.5
Default Emission Factors for LPG (USEPA 1995)

	Controlled HDV (lb/million BTU)	Uncontrolled HDV (lb/million BTU)	Controlled HDV (g/MJ)	Uncontrolled HDV (g/MJ)
CH_4	0.022	0.066	0.0095	0.0284
N_2O				
CO	0.199	3.359	0.0855	1.4438
NMVOC	0.155	1.127	0.0666	0.4844
NOx	0.53	0.796	0.2278	0.3421
CO_2 as C	37.8	37.8	16.2476	16.2476

11.2.2 Upstream

Upstream processing has been dealt with in the description of autogas. The processing of HD5 is identical, except for the rejection of the butane and the subsequent provision of propane gas.

11.3 Results

11.3.1 Emissions per unit energy

Table 11.6
Urban and total life cycle emissions calculated for diesel and propane

Full Lifecycle	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.0858	0.0820
HC total	g HC	0.140	0.103
HC urban	g HC	0.111	0.076
NOx total	g Nox	1.044	0.413
NOx urban	g Nox	0.987	0.361
CO total	g CO	0.253	0.036
CO urban	g CO	0.242	0.026
PM10 total	mg PM10	40.7	6.5
PM10 urban	mg PM10	39.3	5.2
Energy embodied	MJ LHV	1.18	1.09

Table 11.7
Precombustion emissions per MJ for diesel and propane

Precombustion	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.0191	0.0170
HC total	g HC	0.0565	0.101
HC urban	g HC	0.027	0.074
NOx total	g Nox	0.100	0.090
NOx urban	g Nox	0.043	0.038
CO total	g CO	0.023	0.021
CO urban	g CO	0.012	0.011
PM10 total	mg PM10	5.42	5.05
PM10 urban	mg PM10	4	3.72
Energy embodied	MJ LHV	1.18	1.09

Table 11.8
Combustion emissions per MJ for diesel and propane

Combustion	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.067	0.065
HC total	g HC	0.084	0.002
HC urban	g HC	0.084	0.002
NOx total	g NOx	0.944	0.323
NOx urban	g NOx	0.944	0.323
CO total	g CO	0.230	0.015
CO urban	g CO	0.230	0.015
PM10 total	mg PM10	35.26	1.43
PM10 urban	mg PM10	35.26	1.43
Energy embodied	MJ LHV	0	0

Table 11.9
Summary of life cycle emissions per MJ from diesel and propane

		LS diesel	LPG (HD5)
Greenhouse	Precombustion	0.0191	0.0170
Greenhouse	Combustion	0.0667	0.0650
HC total	Precombustion	0.0565	0.1010
HC total	Combustion	0.0835	0.0021
HC urban	Precombustion	0.0271	0.0739
HC urban	Combustion	0.0835	0.0021
NOx total	Precombustion	0.1000	0.0904
NOx total	Combustion	0.944	0.323
NOx urban	Precombustion	0.043	0.038
NOx urban	Combustion	0.944	0.323
CO total	Precombustion	0.0225	0.0205
CO total	Combustion	0.2301	0.0152
CO urban	Precombustion	0.0123	0.0110
CO urban	Combustion	0.2301	0.0152
PM10 total	Precombustion	5.42	5.05
PM10 total	Combustion	35.26	1.43
PM10 urban	Precombustion	4.00	3.72
PM10 urban	Combustion	35.26	1.43
Energy embodied	Precombustion	1.18	1.09

11.3.2 Emissions per unit distance

Table 11.10
Exbodied emissions per km for diesel and propane

Full Lifecycle	Units (per km)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.9250	0.8963
HC total	g HC	1.509	1.133
HC urban	g HC	1.192	0.830
NOx total	g NOx	11.250	4.517
NOx urban	g NOx	10.638	3.939
CO total	g CO	2.723	0.390
CO urban	g CO	2.612	0.286
PM10 total	mg PM10	438.4	70.7
PM10 urban	mg PM10	423.1	56.3
Energy Eembodied	MJ LHV	12.7	11.9

Table 11.11
Precombustion emissions per km for diesel and propane

Precombustion	Units (per km)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.2060	0.1860
HC total	g HC	0.609	1.11
HC urban	g HC	0.292	0.807
NOx total	g NOx	1.080	0.988
NOx urban	g NOx	0.468	0.410
CO total	g CO	0.243	0.224
CO urban	g CO	0.132	0.120
PM10 total	mg PM10	58.4	55.1
PM10 urban	mg PM10	43.1	40.7
Energy embodied	MJ LHV	12.7	11.9

Table 11.12
Emissions from combustion per km for diesel and propane

Combustion	Units	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.719	0.710
HC total	g HC	0.900	0.023
HC urban	g HC	0.900	0.023
NOx total	g NOx	10.177	3.529
NOx urban	g NOx	10.177	3.529
CO total	g CO	2.480	0.166
CO urban	g CO	2.480	0.166
PM10 total	mg PM10	380.00	15.63
PM10 urban	mg PM10	380.00	15.63
Energy embodied	MJ LHV	0	0

Table 11.13
Summary of life cycle emissions per km from diesel and propane

		LS diesel	LPG (HD5)
Greenhouse	Precombustion	0.2060	0.1860
Greenhouse	Combustion	0.7190	0.7103
HC total	Precombustion	0.6090	1.1100
HC total	Combustion	0.9000	0.0231
HC urban	Precombustion	0.2920	0.8070
HC urban	Combustion	0.9000	0.0231
NOx total	Precombustion	1.0800	0.9880
NOx total	Combustion	10.170	3.529
NOx urban	Precombustion	0.468	0.410
NOx urban	Combustion	10.170	3.529
CO total	Precombustion	0.2430	0.2240
CO total	Combustion	2.4800	0.1657
CO urban	Precombustion	0.1320	0.1200
CO urban	Combustion	2.4800	0.1657
PM10 total	Precombustion	58.40	55.10
PM10 total	Combustion	380.00	15.63
PM10 urban	Precombustion	43.10	40.70
PM10 urban	Combustion	380.00	15.63
Energy embodied	Precombustion	12.70	11.90

11.3.3 Uncertainties

In the absence of information on the variability and uncertainties associated with LPG emissions, we assume that the uncertainties are the same as those associated with LNG.

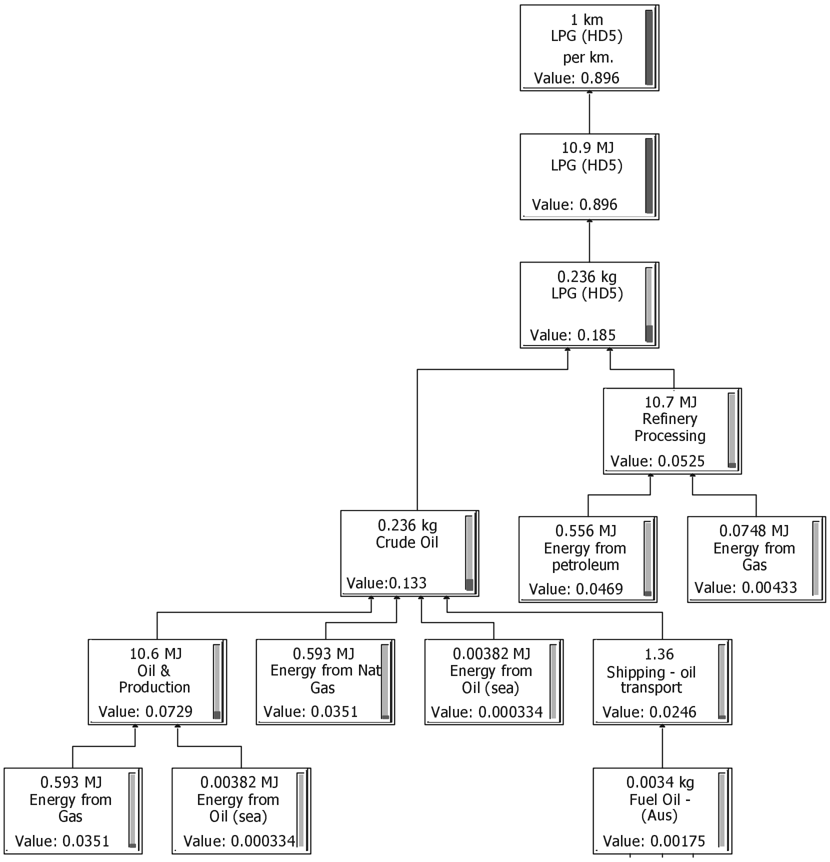


Figure 11.2
Exbodied greenhouse gases emissions (kg CO_2eq) from LPG (HD5) production and processing and use in vehicle

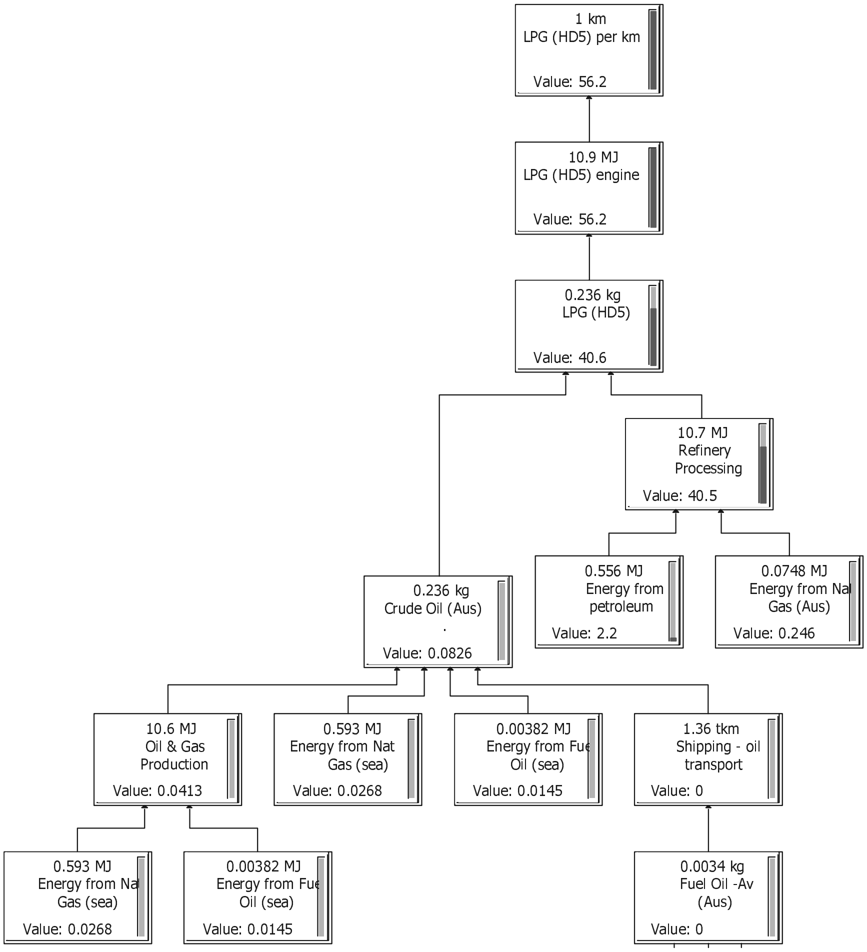


Figure 11.3
Exbodied particulate matter (mg - urban) from LPG (HD5) production and processing and use in vehicle

11.4 Dual fuel and converted vehicles

One relevant issue is a comparison of dual-fuelled vehicles' emissions with those of dedicated LPG only vehicles.

Table 11.14, in the first two columns, gives results reported to the AGO for a 42,000kg GVM 6 cylinder dual fuel (converted) prime mover (when compared to diesel) undergoing tests on the CUEDC drive cycle. Table 11.14 also reproduces the tailpipe results in Table 11.12, in the last two columns. In addition to these results, both maximum power and maximum tractive effort were higher for the dual fuel vehicle.

Table 11.14
Comparative emission (gram per km) for dual fuel and LPG only vehicles

	Dual Fuel		LPG-HD5 only	
	Diesel	**Diesel/LPG**	**Diesel**	**Propane only**
NO_x	18.18	17.67	10.18	3.53
HC	0.69	3.53	0.90	0.023
CO	3.35	8.54	2.48	0.166
CO_2	1296	1359	719	710
PM	0.234	0.227	0.38	0.016

The AGO also provided results (Table 11.15) of tests a Rigid Tray Truck of 13,900 kg GVM that was converted from diesel to a dedicated LPG (HD5) vehicle. The LPG conversion included: modified combustion chambers; reduced compression ratio; sequential port LPG injection; electronic closed loop engine management; and very slight 'lean of stoichiometric' combustion.

The converted vehicle was first tested on the CUEDC cycle. A 3-way catalyst and a turbo boost control valve were then fitted and the vehicle retested in a DT80 test. No testing was done on this vehicle prior to conversion.

Table 11.15
Comparative emission for converted LPG-HD5 only vehicles

	Converted vehicle		Diesel comparison	
	CUEDC (no emission control)	**DT80 (3C+turbo boost)**	**Diesel similar to tested vehicle**	**Generic diesel (Table 11.12)**
NO_x (g/km)	17.1	6.3	4.33	10.18
HC (g/km)	10.6	1.73	0.5	0.90
CO (g/km)	7.16	0.1	2.29	2.48
CO_2 (g/km)	701		763	719
PM (mg/km)	14.1	2.2	453	380
Fuel L/100km	48.3		33.5	
Average opacity (%)	0.1		4.6	

Technical advice communicated by the AGO indicates that the DT80 procedure produces higher emissions than the CUEDC, though the DT80 results correlate well with CUEDC (National Environment Protection Council, 2001). The results for diesel vehicles tested under the CUEDC and DT80 cycles show higher NOx and HC emissions in the DT80 cycle, but substantially lower CO and PM emissions.

Summary

A dedicated LPG vehicle emits lower quantities of all criteria pollutants and greenhouse gases from its tailpipe than an equivalent diesel vehicle. This advantage is lost with dual fuel vehicles and with converted vehicles. On the basis of the two test for which data was available, total hydrocarbon emissions from both types of vehicles are higher than those of the equivalent diesel vehicles. The dual fuel vehicle emitted higher quantities of CO and CO_2 (as well as HC) than the equivalent diesel vehicle.

The three way catalyst and turbo boost reduced NOx, HC, CO and PM emissions. However, the converted propane vehicle emitted higher quantities of NOx, as well as HC, (when compared to an equivalent diesel vehicle) even when fitted with a three way catalyst, though the three way catalyst and turbo boost was very successful in reducing CO emissions. Neverthless, in all cases the change from diesel to LPG – whether from dedicated, converted or dual fuel vehicles - results in lower particulate matter (PM) emissions.

The Australian LPG conversion industry for heavy vehicles is at an early stage in its development. The data from these two tests may not reflect the emissions performance of converted vehicles in the longer term.

11.5 Viability and Functionality

Propane (HD5) viability and functionality issues are identical to those of autogas. The main benefit of propane is that the compression ratio can be altered to suit the higher octane fuel.

Stakeholder input from Cummins noted that when comparing diesel, propane and natural gas in the same engine then the engine performance ratings are highest for diesel, then CNG, then propane. The use of an exhaust brake (guillotine style) is not permitted with the propane or CNG engine, due to the high exhaust temperature. The results, as provided, are reproduced in Table 11.14.

Table 11.16
Relative performance of a Cummins 5.9 L engine

	Maximum bhp rating	Maximum torque
Diesel	260	660
Propane	195	420
CNG/LNG	230	500

Source: J. Bortolussi (pers. comm.)

11.6 Health Effects

Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles. LPG in liquid form can cause cold-burns to the skin in case of inappropriate use. In general, the health effects of autogas and HD5 are the same.

11.6.1 Production and transport

LPG’s low emissions have low greenhouse gas effects and low NOx precursors.

Particulate Matter

The LCA estimate for LPGHD5 urban precombustion (truck) PM10 emissions of 41 mg/km is similar to the LSD estimate of 43 mg/km.

Air Toxics

The LCA estimate for LPGHD5 urban precombustion (truck) HC emissions of 0.807 g/km is greater than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

11.6.2 Use

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics.

LPG, like CNG, has much lower emissions than diesel, and LPG has low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost. (Anyon 1998).

Anyon (1998) also points out that US tests on medium-large engines also confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 11.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km.

Particulate matter

Research consistently shows that LPG (and gaseous fuels in general) with its simple chemistry and very low sulphur content, emit extremely low levels of particulates. (Anyon, 1998).

The LCA estimate for LPGHD5 combustion (truck) PM10 emissions of 16 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

LPG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998).

The LCA estimate for LPGHD5 combustion (truck) HC emissions of 0.023 g/km is substantially less than the LSD estimate of 0.900 g/km.

11.6.3 Summary

LPGHD5 upstream emissions of particulates are similar to LSD. LPGHD5 upstream emissions of air toxics are greater than LSD. LPGHD5 tailpipe emissions of particulates are substantially less than LSD. LPCNG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for LPGHD5 and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

11.7 Environmental Issues

The environmental issues related to propane will be identical to those related to autogas.

Propane may be thought of as a natural gas by-product, or as a petroleum refinery by-product. In the former case the upstream environmental issues are those of CNG; whereas in the latter case the environmental issues are those of diesel.

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

11.8 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 11.1 lists the estimated emissions factors for LPG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of LPG. The estimates of Arcoumanis (2000) indicate that LPG can be expected to meet all future Australian Design Rules for all pollutants.

Table 11.17

Estimated emission factors for LPG under future technologies

Technology	CO	CO	HC	HC	NO_x	NO_x	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.4	**1.0**	0.5	**1.0**	0.3	**1.0**	0.3	1.1	1.2
Euro3	**0.53**	0.2	**0.6**	0.3	**0.71**	0.2	**0.67**	0.2	1.0	1.2
Euro4	**0.38**	0.1	**0.42**	0.1	**0.5**	0.2	**0.2**	0.05	1.0	1.1

11.9 Summary

11.9.1 Advantages

- Propane has low cold-start emissions due to its gaseous state.
- Propane has lower peak pressure during combustion than conventional fuels, which generally reduces noise and improves durability.
- LPG fuel systems are sealed and evaporative losses are negligible.
- Propane is easily transportable and offers ‘stand-alone’ storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- Propane contains negligible toxic components.
- LPG has lower particulate emissions and lower noise levels relative to diesel, making propane attractive for urban areas. Noise levels can be less than 50% of equivalent engines using diesel.
- Propane’s emissions are low in greenhouse gases and low in NOx, thus they are low in ozone precursors.
- Increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

11.9.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low which explains why LPG tanks take more space and weigh more than diesel fuel tanks of the same energy storage capacity.
- Propane is heavier than air, which requires appropriate handling.
- Though the lower flammability limit for propane is actually higher than the lower flammability limit for petrol, the vapour flammability limits in air are wider than those of petrol, which makes propane ignite more easily.
- Propane has a high expansion coefficient so that tanks can be filled to only 80% of capacity.
- LPG in liquid form can cause cold burns to the skin in case of inappropriate use.

12. Premium Unleaded Petrol

12.1 Introduction

The study brief requires an examination of premium unleaded petrol (PULP) (95 RON) meeting either the Euro2 specification for unleaded petrol or the fuel specifications for PULP proposed by the Commonwealth for implementation in 2002. It is assumed that this fuel does not contain ethanol and that it is used in light vehicles as defined in ADR 79/00 and 79/01. The emission limits specified in these ADRs may be found at:

http://www.dotrs.gov.au/land/environment/emissionrequirements.pdf

Our analysis is thus based on a hypothetical vehicle that satisfies Euro2 tailpipe emissions. PULP will thus be used as a reference fuel with which to compare emissions from the use of anhydrous ethanol in PULP.

12.2 Full Fuel-Cycle Analysis

12.2.1 Tailpipe emissions

We take tailpipe emissions for the hypothetical vehicle to be those of a Euro2 vehicle as given by http://www.dotrs.gov.au/land/environment/emissionrequirements.pdf:

CO	2.2 g/km
HC	0.28 g/km
NOx	0.22 g/km
PM	0.08 g/km,

with an additional requirement that there be less than 2 g/km evaporative emissions.

Further, we follow Louis (2001) and take these values as appropriate to a Mercedes A-class 1.6 L reference vehicle. The fuel consumption of this vehicle is 7.5 L per 100 km (13.33 km/L), which corresponds to a fuel energy use of 2.42 MJ/km. According to Louis (2001) this corresponds to 172 g/km emissions of greenhouse gases from such a vehicle when using petrol.

12.2.2 Upstream

Production of ULP and PULP

Petrol is manufactured using a number of refinery product streams derived from crude oil. The blending process is generally determined by three major factors: specification requirements, availability of specific process units within particular refinery configuration, and the properties of the crude oil used.

There are two grades of unleaded petrol manufactured in Australia for use in vehicles – regular unleaded (ULP) and premium unleaded (PULP). The most important parameters for both grades are summarised in Table 12.1.

Table 12.1
Unleaded petrol specifications

Petrol grade	Property	Minimum	Maximum
Regular	MON	82	N/a
	RON	91	93
	FVI	80	106
	Sulfur	N/a	500 ppm
Premium	MON	82	N/a
	RON	95	N/a
	FVI	80	106
	Sulfur	N/a	500 ppm

Both grades have the same requirement for motor octane number (MON). Research octane number (RON) requirement is higher for PULP. The determination of both the RON and the MON is done using standard test engines under strict conditions defined in the relevant specifications. RON test reflects anti-knock properties at lighter load, while MON is determined under conditions resembling high power demand under heavy load.

Flexible volatility index (FVI) is related to vapour pressure of petrol at various temperatures. Variations in FVI are seasonal – FVI requirement changes every month and this variation is a reflection of the average ambient temperatures within different geographic regions at different times of the year. Sulfur content is generally limited to 500 ppm (w/w), with excursions of up to 1000 ppm allowable under specific conditions.

Hydrocarbons constituting petrol can be broadly broken into three categories: paraffins, naphthenes and aromatics. Generally the octane rating of those increases with increasing chain branching, unsaturation and aromaticity. Variation of octane rating and volatility between different hydrocarbon types is the basis for the blending process. The objective is to produce petrol up to the specification while maximising efficiency of the refining process and feedstock utilisation.

An example of crude oil processing is presented in the chapter describing diesel fuel production. The first stage of crude oil processing is atmospheric pressure distillation. Fraction boiling between 90^{o}C and 220^{o}C, called straight run naphtha (gasoline), is the basic feedstock used in petrol production. It consists of predominantly straight chain aliphatic hydrocarbons. Its octane rating is generally below specification and needs to be adjusted by further processing. The first processing step is usually hydrotreating, which lowers sulfur contents and reduces unsaturation.

A number of processes are used to produce blending components. These typically include:

- Reforming – thermal catalytic isomerisation and aromatisation of paraffins and naphthenes, which increases octane rating.
- Isomerisation – conversion of paraffins to isoparaffins in the presence of hydrogen and the catalyst.
- Cracking – thermal catalytic breaking of heavy fractions which produces a broad range of highly aromatic fractions.
- Alkylation/polymerisation – catalytic oligomerisation of light olefines producing isoparaffins.

The difference between ULP and PULP is determined by differences in octane rating. PULP blend typically contains a larger proportion of high octane streams, i.e those containing aromatics, isoparaffins and naphthenes.

Upstream emissions in petrol production arise from oil recovery, transportation and processing. Further emissions derive from the distribution through the retail network.

12.3 Results

The upstream emissions results are based on the energies involved in typical refining operations (as evaluated for low sulfur diesel).

12.3.1 Emissions per unit energy

Table 12.2
Exbodied emissions per MJ for PULP

Full Lifecycle	**Units**	**PULP**
Greenhouse	kg CO_2	0.0888
HC total	g HC	0.170
HC urban	g HC	0.141
NOx total	g NOx	0.185
NOx urban	g NOx	0.129
CO total	g CO	0.930
CO urban	g CO	0.920
PM10 total	mg PM10	38.2
PM10 urban	mg PM10	36.9
Energy embodied	MJ LHV	1.14

Table 12.3
Precombustion emissions per MJ for PULP

Precombustion	**Units**	**PULP**
Greenhouse	kg CO_2	0.0177
HC total	g HC	0.0543
HC urban	g HC	0.026
NOx total	g NOx	0.094
NOx urban	g NOx	0.038
CO total	g CO	0.021
CO urban	g CO	0.011
PM10 total	mg PM10	5.19
PM10 urban	mg PM10	3.8
Energy embodied	MJ LHV	1.14

Table 12.4
Combustion emissions per MJ for PULP

Combustion	Units	PULP
Greenhouse	kg CO_2	0.071
HC total	g HC	0.116
HC urban	g HC	0.116
NOx total	g NOx	0.091
NOx urban	g NOx	0.091
CO total	g CO	0.909
CO urban	g CO	0.909
PM10 total	mg PM10	33.06
PM10 urban	mg PM10	33.06
Energy embodied	MJ LHV	0

Table 12.5
Summary of exbodied emissions per MJ for PULP

		PULP
Greenhouse kg	Precombustion	0.0177
Greenhouse kg	Combustion	0.0711
HC total g	Precombustion	0.0543
HC total g	Combustion	0.1157
HC urban g	Precombustion	0.0257
HC urban g	Combustion	0.1157
NOx total g	Precombustion	0.0937
NOx total g	Combustion	0.091
NOx urban g	Precombustion	0.038
NOx urban g	Combustion	0.091
CO total g	Precombustion	0.0212
CO total g	Combustion	0.9091
CO urban g	Precombustion	0.0113
CO urban g	Combustion	0.9091
PM10 total mg	Precombustion	5.19
PM10 total mg	Combustion	33.06
PM10 urban mg	Precombustion	3.80
PM10 urban mg	Combustion	33.06
Energy embodied MJ	Precombustion	1.14

12.3.2 Emissions per unit distance

Table 12.6
Exbodied emissions per km for PULP

Full Lifecycle	Units	PULP
Greenhouse	kg CO_2	0.2148
HC total	g HC	0.412
HC urban	g HC	0.342
NOx total	g NOx	0.447
NOx urban	g NOx	0.313
CO total	g CO	2.251
CO urban	g CO	2.227
PM10 total	mg PM10	92.5
PM10 urban	mg PM10	89.2
Energy embodied	MJ LHV	2.75

Table 12.7
Precombustion emissions per km for PULP

Precombustion	Units	PULP
Greenhouse	kg CO_2	0.0428
HC total	g HC	0.132
HC urban	g HC	0.062
NOx total	g NOx	0.227
NOx urban	g NOx	0.093
CO total	g CO	0.051
CO urban	g CO	0.027
PM10 total	mg PM10	12.5
PM10 urban	mg PM10	9.19
Energy embodied	MJ LHV	2.75

Table 12.8
Tailpipe emissions per km for PULP

Combustion	Units	PULP
Greenhouse	kg CO_2	0.172
HC total	g HC	0.280
HC urban	g HC	0.280
NOx total	g NOx	0.220
NOx urban	g NOx	0.220
CO total	g CO	2.200
CO urban	g CO	2.200
PM10 total	mg PM10	80.00
PM10 urban	mg PM10	80.00
Energy embodied	MJ LHV	0

Table 12.9
Summary of exbodied emissions per km for PULP

		PULP
Greenhouse kg	Precombustion	0.0428
Greenhouse kg	Combustion	0.1720
HC total g	Precombustion	0.1320
HC total g	Combustion	0.2800
HC urban g	Precombustion	0.0622
HC urban g	Combustion	0.2800
NOx total g	Precombustion	0.2270
NOx total g	Combustion	0.220
NOx urban g	Precombustion	0.093
NOx urban g	Combustion	0.220
CO total g	Precombustion	0.0513
CO total g	Combustion	2.2000
CO urban g	Precombustion	0.0272
CO urban g	Combustion	2.2000
PM10 total mg	Precombustion	12.50
PM10 total mg	Combustion	80.00
PM10 urban mg	Precombustion	9.19
PM10 urban mg	Combustion	80.00
Energy embodied MJ	Precombustion	2.75
Greenhouse kg	Combustion	0

12.3.3 Uncertainties

We will assume that the uncertainties are the same as those associated with low sulfur diesel.

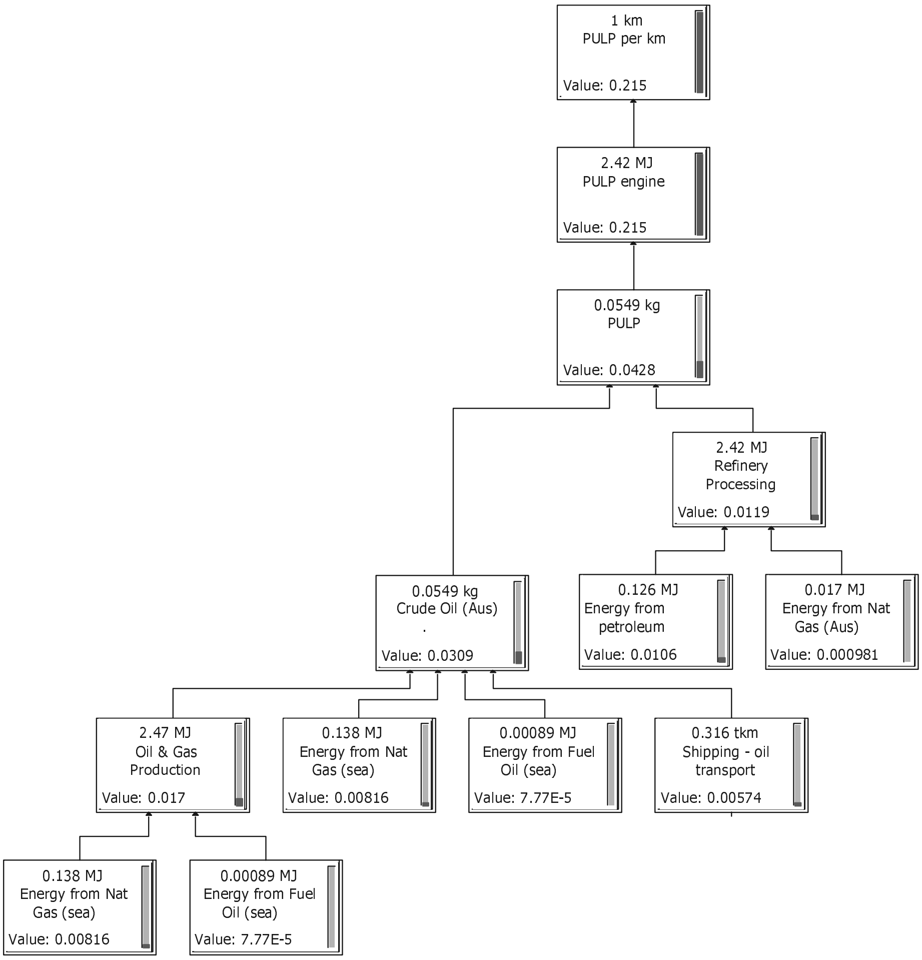


Figure 12.1
Exbodied greenhouse gases emissions (kg CO_2eq) from PULP production and processing and use in vehicle

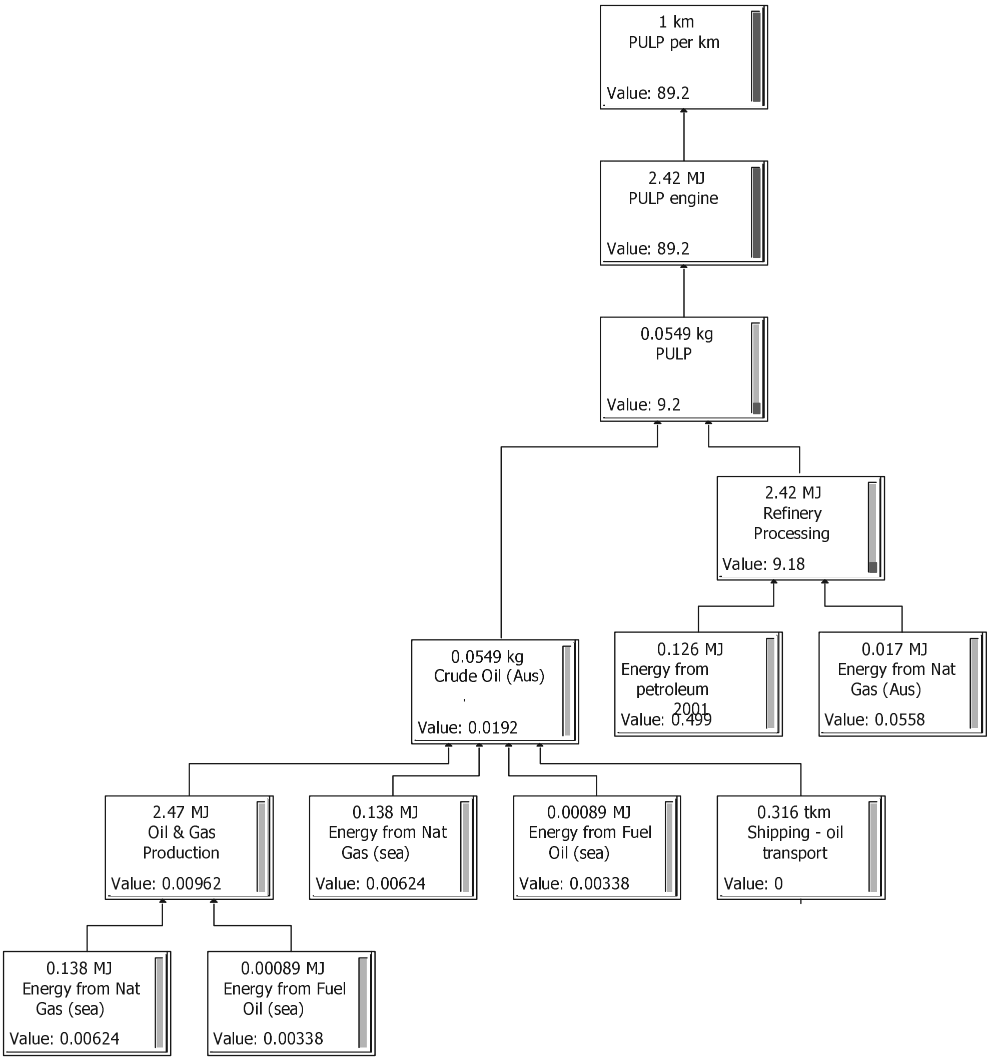


Figure 12.2
Exbodied particulate matter (mg - urban) from PULP production and processing and use in vehicle

12.4 Viability and Functionality

Petrol is the most common automotive fuel, and unleaded petrol has been in use in Australia since 1986. Manufacturers produce premium unleaded petrol and its use does not cause warranty problems. Vehicle operational range depends on the size of the fuel tank, but typical values for a four or six cylinder car range from 400 to 600 km.

During consultation with stakeholders we were informed that there are considerable benefits arising from the widespread use of Euro4 quality RON petrol over 91 RON petrol. The improvement in fuel efficiency available for cars tuned for 95 octane is of the order of 2 to 4% over engines tuned for 91 octane. There is thus scope for smaller engines using 95 RON to have similar performance to engines tuned for 91 RON fuel.

All forms of petrol are considered hazardous according to Worksafe Australia criteria; more so than diesel fuel. Petrol has an extreme flammability rating and extreme chronic effect rating. It has moderate toxicity and body contact ratings.

PULP properties (Louis, 2001) are a density of 749 g/L and a LHV 43.1 MJ/kg.

12.5 Health Issues

Petrol is flammable, carcinogenic, and potentially addictive when inhaled (petrol sniffing). A typical material data safety sheet notes that unleaded petrol is:

- Highly flammable.
- Harmful by inhalation, in contact with skin and if swallowed.
- May cause cancer.
- Danger of serious damage to health by prolonged exposure.
- Harmful-petrol may cause lung damage if swallowed.
- May produce discomfort of the eyes and respiratory tract*.
- Repeated exposure potentially causes skin dryness and cracking*.
- Vapours potentially cause drowsiness and dizziness*.

Table 12.10
Summary of air toxics emissions of PULP per km

Substance	Unit	PULP
Benzene (tailpipe)	mg	0.0768
Benzene (sea)	µg	0.268
Formaldehyde	mg	0.0148
Formaldehyde (sea)	µg	9.6
PAH (total)	µg	0.511
PAH (sea)	µg	0.0948
PAH (tailpipe)	µg	0.0071
Toluene (total)	mg	0.386
toluene (sea)	µg	0.467
Xylenes (total)	mg	0.153

12.5.1 Production and transport

Particulate matter

The LCA estimate for PULP urban precombustion (car) PM10 emissions is 9 mg/km.

Air toxics

The LCA estimate for PULP urban precombustion (car) HC emissions is 0.062 g/km. The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

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* There is limited evidence for these effects

12.5.2 Use

Particulate matter

The LCA estimate for PULP combustion (car) PM10 emissions is 80 mg/km.

Air toxics

The LCA estimate for PULP combustion (car) HC emissions is 0.280 g/km.

12.6 OHS Issues

The OHS issues in the lifecycle of PULP are well known and covered by a range of State and Commonwealth occupational health and safety provisions.

12.7 Vapour Pressure Issues

Evaporative emissions are a considerably more important issue for petrol or gasoline fuelled vehicles, than for diesel vehicles. There is evidence (see for example NRC, 1991) that evaporative emissions have been consistently under-estimated, and recent studies have continued to demonstrate the importance of evaporative emissions.

At a 1999 US workshop sponsored by the Coordinating Research Council (CRC) on On-Road Vehicle Emissions, (a summary is available at:

http://www.crcao.com/crcwebpage/reports/recent%20studies/9onroad%20workshop%20summary.pdf

Bob Gorse of the Ford Motor Company summarised results from several CRC and the Auto/Oil Air Quality Improvement Research Program vehicle evaporative emissions studies. Hot-soak, diurnal, and running loss emissions were evaluated using in-use passenger cars and light trucks captured at I/M lanes in Phoenix, using tank fuels during summer periods. The hot-soak study tested 300 1983-1993 model year vehicles; the diurnal study tested 150 1971-1991 model year vehicles, and the running loss study tested 151 1971-1991 model year vehicles. A new vehicle evaporative emissions program tested 50 1992- 1997 model year vehicles for hot-soak, diurnal and running loss emissions. The combined results from these studies of in-use vehicles by model year groups suggest that evaporative emissions may be equal in mass emission rates to those from exhaust emissions, and concludes that further emphasis should be placed on evaporative emissions studies in the future.

The CRC/Auto-oil study considers three sources of evaporative losses from vehicles: diurnal, hot-soak and running loss emissions. Running loss emissions have not been extensively characterised, but there is evidence (see, for example, Duffy *et al*, 1999) that diurnal emissions are enriched in the more volatile components of the fuel, and that hot-soak emissions have a composition close to that of the parent gasoline. This suggests that hot soak losses are a consequence of essentially complete evaporation of the fuel, whereas diurnal losses arise from vaporisation of the lighter, more volatile components.

12.8 Environmental Impact and Benefits

Ecologically sustainable development (ESD) is based on the principles of equity, efficiency and ecological integrity. The modern western economy is based on petroleum products, of which petrol, unleaded petrol, and premium unleaded petrol are examples. Though substantial arguments can be advanced that such an economy is not sustainable, in the sense that fossil fuels constitute a non-renewable resource, over the past three decades exploration activity has continually discovered new hydrocarbon reserves. In addition, the current concern over climate change has highlighted the burning of fossil fuels as one of the main causes. Thus even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity.

Petrol is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from petrol itself can also occur, especially from leaks, at service stations and refuelling depots, which have been known to contaminate groundwater supplies.

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13. Anhydrous Ethanol

13.1 Background

Development and use of alcohol fuels in transport have for the most part been driven by the desire in many countries to find renewable substitutes for imported petroleum-based fuels. Alcohol fuels have also been used as additives to conventional fuels to improve fuel characteristics. For petrol blends, ethanol is a known octane enhancer (a component added to petrol to increase octane rating and reduce engine knock) and oxygenate (a fuel or fuel additive containing hydrogen, carbon and oxygen in its molecular structure). Ethanol will easily blend with gasoline but blending with diesel requires an emulsifier or additive to form a stable fuel. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations.

More recently alcohol fuels have been the focus of attention as a possible means of reducing greenhouse gas emissions, and noxious urban emissions from transport. Results from several studies that have been conducted thoughout the world on exhaust emissions from ethanol blended fuels are often contradictory, making it difficult to generalise on emission outcomes and performance of ethanol blends. Furthermore, the tailpipe emissions from ethanol blended fuels varies markedly between different ethanol blends and different vehicle technologies.

Ethanol can be produced in two forms – hydrated and anhydrous. Hydrated ethanol has a purity of 95% suitable for blending with an ignition improver, or as a 15% emulsion in diesel that is known as diesohol. A second stage refining process is required to produce anhydrous ethanol (100% purity) for use in ethanol blends in petrol. Most industrial ethanol is denatured (to prevent oral consumption) by the addition of small amounts of an unpleasant or poisonous substance.

Anhydrous ethanol can be used as an additive in petrol, or as a fuel in its own right. Despite this, as an automotive fuel it is usually composed of 85% ethanol with 15% petrol (E85P) and this is the fuel that will be examined in this chapter. The reason for this is that the addition of 15% petrol improves the ignitability of alcohol, especially at low temperature. Other additives have also been trialled as ignition improvers. Ethanol is probably the most widely used alternative automotive fuel in the world, mainly due to Brazil’s decision to produce fuel alcohol from sugar cane. Previous chapters have discussed diesohol, petrohol, and hydrated ethanol (for heavy vehicles). Because the only differences between hydrated and anhydrous ethanol are (i) the extra energy required for distillation, and (ii) the absence of an emulsifier when the anhydrous ethanol is blended with petrol, this chapter will deal with the use of anhydrous ethanol as a fuel for cars.

13.2 Full Fuel-Cycle Emissions

The upstream emissions associated with anhydrous ethanol are essentially the same as those associated with hydrated ethanol, with a requirement for extra energy input arising from the extra process step to transform the hydrated ethanol to anhydrous ethanol. According to Table 10 of the chapter on hydrated ethanol, 30% more energy is needed to convert hydrated ethanol to anhydrous ethanol. Our calculations also include the emissions associated with the production of the 15% of petrol added to the anhydrous ethanol.

13.2.1 Tailpipe emissions

Table 13.1 gives the tailpipe emissions (in kg) over the life of a typical vehicle using petrol and using oxygenated petrol (Maclean, 1998; 2000)

Table 13.1
Lifetime exhaust emissions (kg) of air pollutants and carbon dioxide from petrol and oxygenated petrol

	NMHC	CO	NOx	PM	THC	CO_2
Petrol	36	494	58	12	60	53,676
E85P	35±35	536±484	38±38		66±66	48,564*

*Renewable carbon, 85% of which is not considered to be a greenhouse gas.

These results agree with those of Arcoumanis (2000) who examined ethanol fuel for passenger cars and noted that tailpipe emissions of CO and hydrocarbons were 10% above Euro2 standards, NOx was 20% below Euro2, CO_2 emissions were comparable, but particulate matter emissions were about half those of petrol vehicles.

13.3 Results

Wang et al. (1999) conducted a detailed study of the use of corn ethanol in the United States in terms of full fuel cycle energy and greenhouse gas emissions. Representative values for the results for the life cycle emissions associated with the use of anhydrous ethanol may be found in the chapter on hydrated ethanol. These may be taken as representative values when considered on a g/MJ, or g/km basis. When anhydrous ethanol is used in automobiles, the results will differ when expressed on a g/t-km basis. The variability and uncertainties associated with both forms of ethanol are expected to be the same.

13.3.1 Emissions on a mass per unit energy basis

Table 13.2
Exbodied emissions per MJ for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Full Lifecycle	Units	PULP	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0888	0.0440	0.0679	0.0401	0.0651	0.0364	0.0173	0.1464
HC total	g HC	0.170	0.136	0.134	0.128	0.180	0.903	0.556	0.572
HC urban	g HC	0.141	0.126	0.126	0.120	0.126	0.849	0.548	0.507
NOx total	g NOx	0.185	0.186	0.185	0.162	0.325	0.276	0.128	0.343
NOx urban	g NOx	0.129	0.148	0.168	0.147	0.182	0.133	0.113	0.297
CO total	g CO	0.930	1.438	1.562	1.000	1.606	3.916	2.476	1.044
CO urban	g CO	0.920	1.431	1.558	0.997	1.002	3.306	2.476	1.028
PM10 total	mg PM10	38.2	35.0	34.5	51.2	53.5	72.9	55.0	38.3
PM10 urban	mg PM10	36.9	34.2	34.1	50.8	51.0	70.3	54.6	37.5
Energy embodied	MJ LHV	1.14	0.61	0.66	0.62	0.85	0.94	2.40	3.00

Table 13.3
Precombustion emissions per MJ for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Precombustion	**Units**	**PULP**	**Ethanol azeotropic (molasses-expanded sys.bound.)**	**Ethanol azeotropic (molasses-economic allocation)**	**Ethanol azeotropic (wheat starch waste)**	**Ethanol azeotropic (wheat)**	**Ethanol azeotropic (wheat) fired with wheat straw**	**Ethanol azeotropic (woodwaste)**	**Ethanol azeotropic (ethylene)**
Greenhouse	kg CO_2	0.0177	0.0377	0.0616	0.0338	0.0588	0.0301	0.0110	0.0821
HC total	g HC	0.0543	0.0231	0.0219	0.0158	0.0673	0.791	0.444	0.46
HC urban	g HC	0.026	0.013	0.014	0.008	0.014	0.737	0.436	0.395
NOx total	g NOx	0.094	0.126	0.125	0.102	0.265	0.216	0.068	0.283
NOx urban	g NOx	0.038	0.088	0.108	0.087	0.122	0.073	0.053	0.237
CO total	g CO	0.021	0.452	0.576	0.014	0.620	2.930	1.490	0.058
CO urban	g CO	0.011	0.445	0.572	0.011	0.015	2.320	1.490	0.041
PM10 total	mg PM10	5.19	1.96	1.48	18.1	20.4	39.8	21.9	5.25
PM10 urban	mg PM10	3.8	1.16	1.06	17.7	17.9	37.2	21.5	4.48
Energy embodied	MJ LHV	1.14	0.61	0.66	0.62	0.85	0.94	2.40	3.00

Table 13.4
Combustion emissions per MJ for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Combustion	**Units**	**PULP**	**Anhydrous Ethanol with 15% PULP**
Greenhouse	kg CO_2	0.071	0.006
HC total	g HC	0.116	0.112
HC urban	g HC	0.116	0.112
NOx total	g NOx	0.091	0.060
NOx urban	g NOx	0.091	0.060
CO total	g CO	0.909	0.986
CO urban	g CO	0.909	0.986
PM10 total	mg PM10	33.06	33.06
PM10 urban	mg PM10	33.06	33.06
Energy embodied	MJ LHV	0	0

13.3.2 Vehicle emissions - cars (g/km)

This section gives the calculated values for the emissions from cars, on a per-kilometre basis.

Table 13.5
Exbodied emissions per km for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Full Lifecycle	Units	PULP	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.2148	0.1062	0.1641	0.0969	0.1571	0.0879	0.0417	0.3546
HC total	g HC	0.412	0.328	0.325	0.311	0.435	2.182	1.352	1.382
HC urban	g HC	0.342	0.304	0.306	0.291	0.306	2.052	1.332	1.227
NOx total	g NOx	0.447	0.448	0.446	0.392	0.785	0.668	0.309	0.830
NOx urban	g NOx	0.313	0.358	0.405	0.355	0.439	0.321	0.273	0.718
CO total	g CO	2.251	3.477	3.777	2.421	3.887	9.477	5.997	2.526
CO urban	g CO	2.227	3.467	3.767	2.414	2.424	8.007	5.987	2.487
PM10 total	mg PM10	92.5	84.8	83.6	123.7	129.4	176.2	132.9	92.7
PM10 urban	mg PM10	89.2	82.8	82.6	122.8	123.3	170.1	132.0	90.8
Energy embodied	MJ LHV	2.75	1.48	1.59	1.50	2.05	2.27	5.80	7.26

Table 13.6
Precombustion emissions per km for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Precombustion	Units	PULP	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0428	0.0911	0.1490	0.0818	0.1420	0.0728	0.0266	0.1990
HC total	g HC	0.132	0.0559	0.053	0.0383	0.163	1.91	1.08	1.11
HC urban	g HC	0.062	0.032	0.033	0.019	0.033	1.780	1.060	0.955
NOx total	g NOx	0.227	0.304	0.302	0.248	0.641	0.524	0.165	0.686
NOx urban	g NOx	0.093	0.214	0.261	0.211	0.295	0.177	0.129	0.574
CO total	g CO	0.051	1.090	1.390	0.034	1.500	7.090	3.610	0.139
CO urban	g CO	0.027	1.080	1.380	0.027	0.037	5.620	3.600	0.100
PM10 total	mg PM10	12.5	4.75	3.58	43.7	49.4	96.2	52.9	12.7
PM10 urban	mg PM10	9.19	2.81	2.58	42.8	43.3	90.1	52	10.8
Energy embodied	MJ LHV	2.75	1.48	1.59	1.5	2.05	2.27	5.8	7.26

Table 13.7
Tailpipe emissions per km for premium unleaded petrol (PULP) and ethanol (mixed with 15% PULP)

Combustion	Units	PULP	Ethanol
Greenhouse	kg CO_2	0.172	0.015
HC total	g HC	0.280	0.272
HC urban	g HC	0.280	0.272
NOx total	g NOx	0.220	0.144
NOx urban	g NOx	0.220	0.144
CO total	g CO	2.200	2.387
CO urban	g CO	2.200	2.387
PM10 total	mg PM10	80.00	80.00
PM10 urban	mg PM10	80.00	80.00
Energy embodied	MJ LHV	0	0

13.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 6.19.

Table 13.8
Estimated one standard deviation uncertainties (in percent) for hydrated ethanol emissions

	g/MJ	g/t-km	g/p-km
CO_2	15	15	13
HC	45	17	73
NOx	21	8	35
CO	40	36	46
PM10	46	45	46

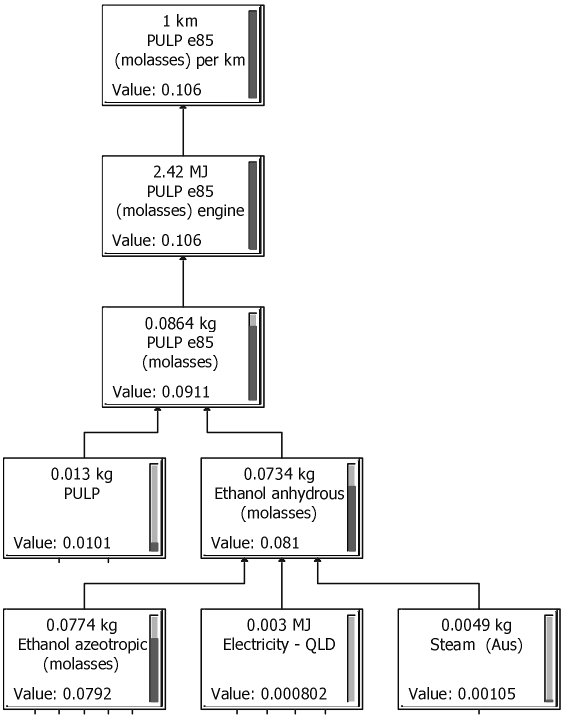

Figure 13.1
Exbodied greenhouse gases emissions (kg CO_2eq) from E85 in PULP production and processing and use in vehicle (Ethanol component is from molasses based on Sarina plant and using expanded system boundary allocation)

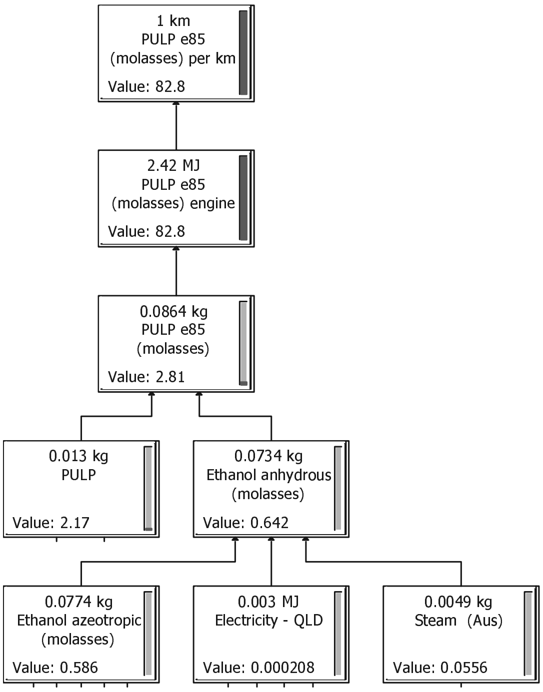

Figure 13.2
Exbodied particulate matter (mg - urban) from E85 in PULP production and processing and use in vehicle (Ethanol component is from molasses based on Sarina plant and using expanded system boundary allocation)

13.4 Viability and Functionality

There is considerable international experience on the use of ethanol in Brazil where sugar-derived ethanol is used as an automotive fuel. The ethanol used in Brazil is called Alcool and consists of 93% ethanol by volume. IEA Alternative Fuels Information Service (1996) note that "the techniques for the production and use of methanol and ethanol as a vehicle fuel are known. Obstacles that hinder the use of alcohols as a vehicular fuel are the relatively high costs of alcohol and the investments necessary to introduce an extra fuel."

The viability and functionality issues related to ethanol and its use in heavy vehicles (as diesohol) or in light vehicles (as petrohol) have been examined in previous chapters, and the same considerations will apply.

13.5 Health and OHS

Table 13.9 gives the exhaust emissions of air toxics given by MacLean (1988) that may also be found in the supporting documentation of MacLean and Lave (2000). The air toxic emissions are given in terms of mass emitted per vehicle lifetime, but are also given in terms of weighted emissions in terms of sulfuric acid equivalents. In both cases, ethanol produces a marked decline in the emissions of air toxics, except for the aldehydes but when their weighting factors are applied, the weighted air toxics emissions from ethanol are below those of petrol. For comparison, the weighted emissions for diesel exhaust are estimated to range from 37,000 to 80,000 grams sulfuric acid equivalent per lifetime.

Table 13.9
Lifetime exhaust emissions (g) of air toxics from petrol and ethanol, along with weighted toxic emissions (grams sulfuric acid equivalent)

	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Aggregate toxics
Petrol	1820	210	350	126	2506
CMU-ET weighted	1138	48	389	0.4	1575
E85	252	28	574	3472	4326
CMU-ET weighted	158	6.4	638	9.6	812

Ethanol fuels perform better than conventional fuels in terms of lower emissions of air toxics, except for aldehydes.

13.6 Environmental Issues

Environmental and ESD issues related to ethanol have been dealt with in Chapter 6. Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid.

When ethanol is derived from a renewable source than the greenhouse gas emissions from ethanol are lower than those of petrol because of the use of a renewable fuel in the blend. The particulate emissions are lowered as are the emissions of ozone precursors. The concentrations of emitted air toxics are lower from ethanol than from petrol.

13.7 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 13.10 lists the estimated emissions factors for ethanol. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of ethanol. The estimates of Arcoumanis (2000) indicate that ethanol can be expected to meet all future Australian Design Rules for all pollutants, except for hydrocarbon emissions.

Table 13.10
Estimated emission factors for ethanol (E85P) under future technologies (PM is unregulated)

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	1.1	**1.0**	1.1	**1.0**	0.8		0.5	**1.0**	0.3
Euro3	**1.05**	0.9	**0.59**	0.8	**0.6**	0.5		0.5	**1.0**	0.25
Euro4	**0.45**	0.3	**0.29**	0.4	**0.32**	0.3		0.4	**1.0**	0.2

13.8 Summary

13.8.1 Advantages

- As a renewable fuel, anhydrous ethanol made from bio-products, produces less fossil CO_2 than conventional fuels.
- Tailpipe emissions of NOx and PM appear to be lower on average.
- Air toxic levels (except for aldehydes) are lower than those of conventional fuels.

13.8.2 Disadvantages

- Cold starting in cool climates is difficult unless ethanol is blended with petrol as a starting aid, or unless some other starting aid is used.

14. Petrohol

14.1 Background

Anhydrous ethanol can be used as an additive in petrol. We use the term petrohol for a blend of 10% anhydrous ethanol in premium unleaded petrol. The symbols E10P or E10PULP are also used for this fuel, depending on whether it is necessary to specify the type of petrol (P) with which the ethanol is blended. The upstream emissions associated with anhydrous ethanol and with premium unleaded petrol have been dealt with in separate chapters. This chapter will therefore not repeat the upstream production and processing information.

14.2 Full Fuel-Cycle Emissions

There has been substantial US interest in the use of ethanol in cars. The reason for this is that the Californian Government, through their Air Resources Board, requires vehicles to use "reformulated gasoline". Originally such reformulated gasoline could be made by blending MTBE (methyl tertiary-butyl ether) into petrol. Because of the contamination of Californian groundwater with MTBE the Californian Governor ordered the removal of MTBE from petrol and studies on the environmental and health effects of ethanol in petrol. The use of ethanol produces an oxygenated fuel that satisfies the requirements of Californian reformulated gasoline.

Oygenates are added to petrol to improve the anti-knock performance and to reduce emissions. Reuter et al (1992) studied European petrol oxygenated with MTBE, ETBE and ethanol and found that the emissions of oxygenated petrol are independent of the oxygenate that is used.

14.2.1 Tailpipe emissions

Anhydrous ethanol is rarely used as a fuel in its own right, though it is frequently used in a blend of 85% anhydrous ethanol with 15% petrol. Petrohol (petrol and ethanol blends that range from 5% to 26% ethanol) consists of a blend of anhydrous ethanol and petrol. In this chapter we will use the term petrohol (or E10PULP) to refer to 95 RON PULP with a 10% ethanol blend. Such fuel has an oxygen level of 3.5%. Table 1 gives the tailpipe emissions (in kg) over the 300,000 km life of a typical vehicle using petrol and using oxygenated petrol (Maclean, 1998; 2000). These values have been used for the tailpipe emissions in the subsequent full-fuel cycle analysis (with appropriate allowance for the fact that carbon dioxide emitted from any ethanol made from renewable fuels is not considered to be a greenhouse gas).

Table 14.1
Lifetime exhaust emissions (kg) of air pollutants and carbon dioxide from petrol and oxygenated petrol

	NMHC	CO	NOx	PM	THC	CO_2
Petrol	36	494	58	12	60	53676
Oxygenated petrol	27±11	416±248	50±20		46±15	56425±289

14.3 *Results*

14.3.1 Emissions per unit energy

Table 14.2
Exbodied emissions per MJ of petrohol based on ethanol from various feedstocks

Full Lifecycle	Units	PULP	PULP E10P (molasses-exp.sys. bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.0888	0.0895	0.0913	0.0891	0.0911	0.0889	0.0874	0.0974
HC total	g HC	0.170	0.139	0.139	0.138	0.142	0.199	0.172	0.173
HC urban	g HC	0.141	0.111	0.112	0.111	0.112	0.168	0.145	0.141
NOx total	g NOx	0.185	0.175	0.174	0.173	0.185	0.181	0.170	0.186
NOx urban	g NOx	0.129	0.121	0.122	0.121	0.123	0.119	0.118	0.132
CO total	g CO	0.930	0.820	0.830	0.786	0.834	1.014	0.902	0.790
CO urban	g CO	0.920	0.811	0.821	0.777	0.777	0.958	0.893	0.779
PM10 total	mg PM10	38.2	38.0	38.0	39.2	39.4	40.9	39.5	38.2
PM10 urban	mg PM10	36.9	36.6	36.6	37.9	38.0	39.5	38.2	36.9
Energy embodied	MJ LHV	1.14	1.10	1.10	1.10	1.11	1.12	1.23	1.28

Table 14.3
Precombustion emissions per MJ of petrohol based on ethanol from various feedstocks

Precombustion	Units	PULP	PULP E10P (molasses-exp.sys.bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.0177	0.0193	0.0211	0.0189	0.0209	0.0187	0.0172	0.0227
HC total	g HC	0.0543	0.0519	0.0518	0.0513	0.0554	0.112	0.0848	0.086
HC urban	g HC	0.026	0.025	0.025	0.024	0.025	0.081	0.058	0.055
NOx total	g NOx	0.094	0.096	0.096	0.094	0.107	0.103	0.092	0.108
NOx urban	g NOx	0.038	0.042	0.044	0.042	0.045	0.041	0.040	0.054
CO total	g CO	0.021	0.055	0.065	0.021	0.068	0.248	0.136	0.024
CO urban	g CO	0.011	0.045	0.055	0.011	0.012	0.192	0.127	0.014
PM10 total	mg PM10	5.19	4.93	4.9	6.19	6.38	7.89	6.49	5.19
PM10 urban	mg PM10	3.8	3.59	3.58	4.88	4.9	6.41	5.18	3.85
Energy embodied	MJ LHV	1.14	1.10	1.10	1.10	1.11	1.12	1.23	1.28

Table 14.4
Tailpipe emissions per MJ of petrohol based on ethanol from various feedstocks

Combustion	Units	PULP	PULP E10P (molasses-exp.sys.bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.071	0.070	0.070	0.070	0.070	0.070	0.070	0.075
HC total	g HC	0.116	0.087	0.087	0.087	0.087	0.087	0.087	0.087
HC urban	g HC	0.116	0.087	0.087	0.087	0.087	0.087	0.087	0.087
NOx total	g NOx	0.091	0.078	0.078	0.078	0.078	0.078	0.078	0.078
NOx urban	g NOx	0.091	0.078	0.078	0.078	0.078	0.078	0.078	0.078
CO total	g CO	0.909	0.766	0.766	0.766	0.766	0.766	0.766	0.766
CO urban	g CO	0.909	0.766	0.766	0.766	0.766	0.766	0.766	0.766
PM10 total	mg PM10	33.06	33.06	33.06	33.06	33.06	33.06	33.06	33.06
PM10 urban	mg PM10	33.06	33.06	33.06	33.06	33.06	33.06	33.06	33.06
Energy embodied	MJ LHV	0	0	0	0	0	0	0	0

Table 14.5
Summary of exbodied emissions per MJ of petrohol based on ethanol from various feedstocks

		PULP	PULP E10P (molasses-exp.sys.bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	Precombustion	0.0177	0.0193	0.0211	0.0189	0.0209	0.0187	0.0172	0.0227
Greenhouse	Combustion	0.0711	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0747
HC total	Precombustion	0.0543	0.0519	0.0518	0.0513	0.0554	0.1120	0.0848	0.0860
HC total	Combustion	0.1157	0.0868	0.0868	0.0868	0.0868	0.0868	0.0868	0.0868
HC urban	Precombustion	0.0257	0.0247	0.0248	0.0243	0.0248	0.0813	0.0578	0.0545
HC urban	Combustion	0.1157	0.0868	0.0868	0.0868	0.0868	0.0868	0.0868	0.0868
NOx total	Precombustion	0.0937	0.0962	0.0961	0.0944	0.1070	0.1030	0.0917	0.1080
NOx total	Combustion	0.091	0.078	0.078	0.078	0.078	0.078	0.078	0.078
NOx urban	Precombustion	0.038	0.042	0.044	0.042	0.045	0.041	0.040	0.054
NOx urban	Combustion	0.091	0.078	0.078	0.078	0.078	0.078	0.078	0.078
CO total	Precombustion	0.0212	0.0548	0.0645	0.0206	0.0680	0.2480	0.1360	0.0240
CO total	Combustion	0.9091	0.7656	0.7656	0.7656	0.7656	0.7656	0.7656	0.7656
CO urban	Precombustion	0.0113	0.0451	0.0551	0.0112	0.0116	0.1920	0.1270	0.0136
CO urban	Combustion	0.9091	0.7656	0.7656	0.7656	0.7656	0.7656	0.7656	0.7656
PM10 total	Precombustion	5.19	4.93	4.90	6.19	6.38	7.89	6.49	5.19
PM10 total	Combustion	33.06	33.06	33.06	33.06	33.06	33.06	33.06	33.06
PM10 urban	Precombustion	3.80	3.59	3.58	4.88	4.90	6.41	5.18	3.85
PM10 urban	Combustion	33.06	33.06	33.06	33.06	33.06	33.06	33.06	33.06
Energy embodied	Precombustion	1.14	1.10	1.10	1.10	1.11	1.12	1.23	1.28

14.3.2 *Emissions per unit distance*

Table 14.6
Exbodied emissions per km of petrohol based on ethanol from various feedstocks

Full Lifecycle	Units	PULP	PULP E10P (molasses-exp.sys. bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.2148	0.2164	0.2209	0.2157	0.2204	0.2150	0.2114	0.2358
HC total	g HC	0.412	0.336	0.335	0.334	0.344	0.481	0.415	0.418
HC urban	g HC	0.342	0.270	0.270	0.269	0.270	0.407	0.350	0.342
NOx total	g NOx	0.447	0.423	0.423	0.418	0.449	0.440	0.412	0.453
NOx urban	g NOx	0.313	0.292	0.296	0.292	0.299	0.289	0.285	0.320
CO total	g CO	2.251	1.986	2.009	1.903	2.018	2.454	2.182	1.911
CO urban	g CO	2.227	1.962	1.986	1.880	1.881	2.317	2.159	1.886
PM10 total	mg PM10	92.5	91.9	91.8	95.0	95.4	99.1	95.7	92.6
PM10 urban	mg PM10	89.2	88.7	88.7	91.8	91.9	95.5	92.5	89.3
Energy embodied	MJ LHV	2.75	2.65	2.66	2.65	2.70	2.71	2.99	3.10

Table 14.7
Precombustion emissions per km of petrohol based on ethanol from various feedstocks

Precombustion	Units	PULP	PULP E10P (molasses-exp.sys. bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.0428	0.0466	0.0511	0.0459	0.0506	0.0452	0.0416	0.0550
HC total	g HC	0.132	0.126	0.125	0.124	0.134	0.271	0.205	0.208
HC urban	g HC	0.062	0.060	0.060	0.059	0.060	0.197	0.140	0.132
NOx total	g NOx	0.227	0.233	0.233	0.228	0.259	0.250	0.222	0.263
NOx urban	g NOx	0.093	0.102	0.106	0.102	0.109	0.099	0.096	0.130
CO total	g CO	0.051	0.133	0.156	0.050	0.165	0.601	0.329	0.058
CO urban	g CO	0.027	0.109	0.133	0.027	0.028	0.464	0.306	0.033
PM10 total	mg PM10	12.5	11.9	11.8	15	15.4	19.1	15.7	12.6
PM10 urban	mg PM10	9.19	8.69	8.68	11.8	11.9	15.5	12.5	9.32
Energy embodied	MJ LHV	2.75	2.65	2.66	2.65	2.7	2.71	2.99	3.1

Table 14.8
Tailpipe emissions per km of petrohol based on ethanol from various feedstocks

Combustion	Units	PULP	PULP E10P (molasses-exp.sys. bound.)	PULP E10P (molasses-eco.allocat.)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	kg CO_2	0.172	0.170	0.170	0.170	0.170	0.170	0.170	0.181
HC total	g HC	0.280	0.210	0.210	0.210	0.210	0.210	0.210	0.210
HC urban	g HC	0.280	0.210	0.210	0.210	0.210	0.210	0.210	0.210
NOx total	g NOx	0.220	0.190	0.190	0.190	0.190	0.190	0.190	0.190
NOx urban	g NOx	0.220	0.190	0.190	0.190	0.190	0.190	0.190	0.190
CO total	g CO	2.200	1.853	1.853	1.853	1.853	1.853	1.853	1.853
CO urban	g CO	2.200	1.853	1.853	1.853	1.853	1.853	1.853	1.853
PM10 total	mg PM10	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
PM10 urban	mg PM10	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Energy embodied	MJ LHV	0	0	0	0	0	0	0	0

Table 14.9
Summary of exbodied emissions per km of petrohol

		PULP	PULP E10P (molasses-exp.sys. bound.)	PULP E10P (molasses-eco.allocat)	PULP E10P (wheat starch waste)	PULP E10P (wheat)	PULP E10P (wheat WS)	PULP E10P (wood waste)	PULP E10P (ethylene)
Greenhouse	Precombustion	0.0428	0.0466	0.0511	0.0459	0.0506	0.0452	0.0416	0.0550
Greenhouse	Combustion	0.1720	0.1698	0.1698	0.1698	0.1698	0.1698	0.1698	0.1808
HC total	Precombustion	0.1320	0.1260	0.1250	0.1240	0.1340	0.2710	0.2050	0.2080
HC total	Combustion	0.2800	0.2100	0.2100	0.2100	0.2100	0.2100	0.2100	0.2100
HC urban	Precombustion	0.0622	0.0599	0.0600	0.0589	0.0600	0.1970	0.1400	0.1320
HC urban	Combustion	0.2800	0.2100	0.2100	0.2100	0.2100	0.2100	0.2100	0.2100
NOx total	Precombustion	0.2270	0.2330	0.2330	0.2280	0.2590	0.2500	0.2220	0.2630
NOx total	Combustion	0.220	0.190	0.190	0.190	0.190	0.190	0.190	0.190
NOx urban	Precombustion	0.093	0.102	0.106	0.102	0.109	0.099	0.096	0.130
NOx urban	Combustion	0.220	0.190	0.190	0.190	0.190	0.190	0.190	0.190
CO total	Precombustion	0.0513	0.1330	0.1560	0.0499	0.1650	0.6010	0.3290	0.0582
CO total	Combustion	2.2000	1.8526	1.8526	1.8526	1.8526	1.8526	1.8526	1.8526
CO urban	Precombustion	0.0272	0.1090	0.1330	0.0272	0.0280	0.4640	0.3060	0.0329
CO urban	Combustion	2.2000	1.8526	1.8526	1.8526	1.8526	1.8526	1.8526	1.8526
PM10 total	Precombustion	12.50	11.90	11.80	15.00	15.40	19.10	15.70	12.60
PM10 total	Combustion	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
PM10 urban	Precombustion	9.19	8.69	8.68	11.80	11.90	15.50	12.50	9.32
PM10 urban	Combustion	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Energy embodied	Precombustion	2.75	2.65	2.66	2.65	2.70	2.71	2.99	3.10

14.3.3 Uncertainties

In the absence of information on the variability and uncertainties associated with E10P emissions, we assume that the uncertainties are the same as those associated with diesohol (E15D).

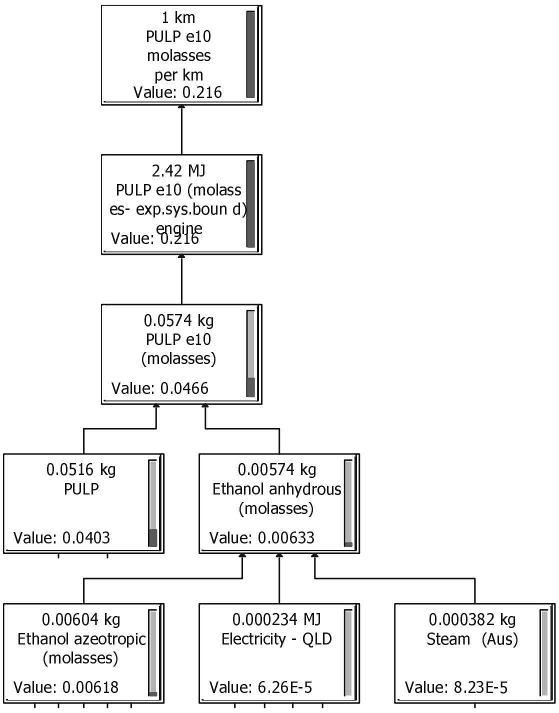

Figure 14.1
Exbodied greenhouse gases emissions (kg CO_2eq) from E10 in PULP production and processing and use in vehicle (Ethanol component is from molasses based on Sarina plant and using expanded system boundary allocation)

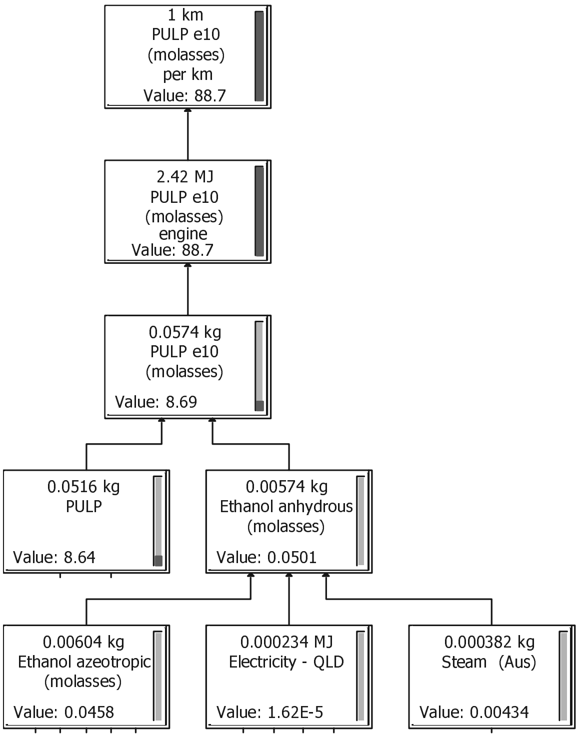

Figure 14.2
Exbodied particulate matter (mg - urban) from E10 in PULP production and processing and use in vehicle (Ethanol component is from molasses based on Sarina plant and using expanded system boundary allocation)

The exbodied greenhouse gas emissions depicted in Figure 14.1 reflect a combination of the fuel economy obtained by using petrohol, and the fact that 10% of the petrohol consists of a renewable fuel whose carbon dioxide emissions are not treated as a greenhouse gas. On the basis of the data in MacLean (1998) the emissions of CO_2 for premium unleaded petrol is 172 g/km whereas for petrohol it is 188 g/km.

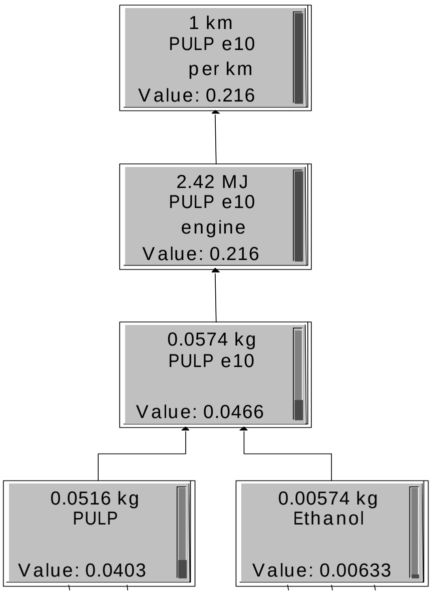

Figure 14.3
Allowing for the renewable components of petrohol means that 216 gram of exbodied greenhouse gases are emitted per kilometre.

Examining Figure 14.3 it may be noted that the tailpipe emissions of greenhouse gases from petrohol come to 170 g/km CO_2-equ. This is from 0.216 – 0.046 kg, as shown in the bottom part of the second and third boxes. The actual tailpipe emissions of CO_2 consist of 170 g/km from the petrol (being 0.9 x 188 g/km), and 11 g from combustion of 5.7 g of ethanol. This comprises 181 g/km.

The expected greenhouse gas saving of 11 g/km by using ethanol does not eventuate because of the altered fuel economy. An equivalent petrol fuelled vehicle emits 172 g/km CO_2-equ. Furthermore, the greenhouse gas benefit of 2 g/km is negated by the greater upstream processing energy in the production of ethanol so that the exbodied greenhouse gas emissions of petrol are 215 g/km whereas those of petrohol are very slightly higher at 216 g/km.

14.4 Viability and Functionality

There is considerable international experience on the use of ethanol as a blend in petrol in the United States, where it is needed under the legislation requiring the use of reformulated gasoline, and in Brazil where sugar derived ethanol is used as an automotive fuel and also as a blend (gasohol). No special engine modification or handling precautions are needed when using a 10% ethanol blend. Such widespread international experience indicates that the viability and functionality of petrohol will be much the same as of the corresponding petrol with which the ethanol is blended.

The web site (http://www.greenfuels.org/ethaques.html) of the Canadian Renewable Fuels Association answers many questions related to the viability and functionality of ethanol in the form of questions and answers. These are reproduced here.

14.4.1 Safety and handling

Is it safe to handle fuel ethanol blends?

The WHMIS Material Safety Data Sheet (MSDS) reveals that the properties of ethanol blends are substantially the same as conventional gasoline blends. Occupational health and safety risks presented by the use of ethanol gasoline do not appear to be any different than those posed by conventional gasoline blends.

Do ethanol blends need special handling or storage?

Only in special circumstances. The gasoline marketer should pump any accumulated water from the storage tank, and add a final filter to the dispensing hose. It is wise also to check seasonally used small engines such as chainsaws and outboard motors (which are more susceptible to water contamination) for the presence of water, and drain the tank if necessary.

14.4.2 Warranty

What is the effect of using ethanol-blended fuels on the manufacturer’s warranty of my vehicle?

When the use of ethanol began in 1979, most automobile manufacturers did not even address alcohol fuels. As soon as each manufacturer tested their vehicles, they approved the use of a 10% ethanol blend. Today, all manufacturers approve the use of 10% ethanol blends, and some even recommend it for environmental reasons.

14.4.3 Functionality

Is it necessary to make changes to my vehicle in order to use ethanol-blended fuels?

All cars built since the 1970s are fully compatible with up to 10% ethanol in the mixture.

Will ethanol-blended fuels work in fuel-injected engines?

Yes. It may be necessary to change the filter more frequently. Ethanol helps to clean out the fuel-injection system, and may aid in the maintenance of a cleaner engine. Since 1985, all ethanol blends and nearly all non-ethanol gasolines have contained detergent additives that are designed to prevent injector deposits. These detergents have been very effective in addressing this issue.

Does ethanol in the fuel work as an effective gas line anti-freeze?

Gas line anti-freeze contains alcohol-usually methanol, ethanol, or isopropyl, which can be used up to a 0.3% level in a car’s fuel tank. All alcohols have the ability to absorb water, and therefore condensation in the fuel system is absorbed and does not have the opportunity to collect and freeze. If an ethanol blend contains 10% ethanol, it is able to absorb more water than a small bottle of isopropyl, and eliminates the need and expense of adding a gas line anti-freeze.

Will ethanol burn valves?

Ethanol will not burn engine valves. In fact, ethanol burns cooler than gasoline. Ethanol high-powered racing engines use pure alcohol for that reason.

Will using ethanol-blended fuels plug the fuel filters in my vehicle?

Ethanol can loosen contaminants and residues that have been deposited by previous gasoline fills. These can collect in the fuel filter. This problem has happened occasionally in older cars, and can easily be corrected by changing fuel filters. Symptoms of a plugged fuel filter will be hesitation, missing, and a loss of power. Once your car’s fuel system is clean, you will notice improved performance.

Can I mix fuels?

Yes. All gasolines in Canada (including low-level ethanol blends) must meet the specifications of the Canadian General Standards Board (CGSB). They are all interchangeable.

Operational range

What is the effect of using ethanol-blended fuels on fuel economy?

Changes in fuel economy are minimal. While a 10% ethanol blend contains about 97% of the energy of ’pure’ gasoline, this is compensated by the fact that the combustion efficiency of the ethanol-blended fuel is increased. The net result is that most consumers do not detect a difference in their fuel economy, although many people using ethanol-blended fuels have said that their fuel economy has improved.

The US National Science and Technology Council (1997) conducted a comprehensive examination of oxygenated fuels and determined that “with regard to fuel economy, the theoretical change in fuel economy as a result of the addition of oxygenates to gasoline is in the range of a 2% to 3% reduction in fuel economy.”

14.5 Health

14.5.1 Production and transport

Anhydrous ethanol can be used as an additive in petrol. The upstream emissions associated with anhydrous ethanol and with premium unleaded petrol have been dealt with in separate chapters. This chapter will therefore not repeat the upstream production and processing information.

Particulate matter
See anhydrous ethanol and PULP sections.
The LCA estimates for E10PULP urban precombustion (car) PM10 emissions are:

- Wheat: 12 mg/km
- Wheat WS: 16 mg/km
- Wheat starch waste: 12 mg/km
- Molasses (alternative allocation): 9 mg/km
- Molasses: 9 mg/km
- Woodwaste: 13 mg/km
- Ethylene: 9 mg/km

Air toxics
See anhydrous ethanol and PULP sections.
The LCA estimates for E10PULP urban precombustion (car) HC emissions are:

- Wheat: 0.060 g/km
- Wheat WS: 0.197 g/km
- Wheat starch waste: 0.059 g/km
- Molasses (alternative allocation): 0.06 g/km
- Molasses: 0.060 g/km
- Woodwaste: 0.140 g/km
- Ethylene: 0.132 g/km

14.5.2 Use

Table 14.1 gives the tailpipe emissions (in kg) over the life of a typical vehicle using petrol and using oxygenated petrol (Maclean, 1998; 2000)

Particulate matter

The estimate for PULP and E10PULP combustion (car) PM10 emissions is 80 mg/km.

Air toxics

Table 14.10 gives the exhaust emissions of air toxics given by MacLean (1988) that may also be found in the supporting documentation of MacLean and Lave (2000). The air toxics emissions are given in terms of mass emitted per vehicle lifetime, but are also given in terms of weighted emissions in terms of sulfuric acid equivalents. In both cases, petrohol produces a marked decline in the emissions of air toxics. For comparison, the weighted emissions for diesel exhaust are estimated to range from 37,000 to 80,000 grams sulfuric acid equivalent per lifetime.

Table 14.10
Lifetime exhaust emissions (g) of air toxics from petrol and oxygenated petrol, along with CMU-ET[1] weighted toxic emissions (grams sulfuric acid equivalent)

	Benzene	1,3-butadiene	Form-aldehyde	Acet-aldehyde	Aggregate toxics
Petrol	1820	210	350	126	2506
CMU-ET weighted	1138	48	389	0.4	1575
Oxygenated petrol	840	126	336	84	1386
CMU-ET weighted	525	29	373	0.2	927

Motor vehicle emissions data indicates that the use of ethanol results in substantial reductions in air toxics emissions. According to the USEPA (1993) substantial reduction in benzene, 1,3 butadiene, refuelling vapours and particulate matter occur, while formaldehyde would be emitted at levels similar to gasoline vehicles. They claim that acetaldehyde emissions may increase substantially, though Table 14.10 does not support this contention.

Oxygenated fuels perform better than conventional fuels in terms of lower emissions of air toxics. Armstrong (2000) reviews the health effects of ethanol vapours coming from ethanol blended petrol and finds no evidence of any health effects. The Californian Office of Environmental Health Hazard Assessment (1999) found similar results. The main thrust of this latter report was to compare ethanol in relation to MTBE as a fuel oxygenate. They concluded that “the direct effects of ethanol (if any public exposure were to occur) would be substantially less severe than the effects of MTBE.”

14.5.3 Summary

E10PULP tailpipe particulate and HC emissions are lower than PULP emissions irrespective of the feedstock. E10PULP tailpipe emissions of benzene, 1,3 butadiene, are substantially less than petrol vehicles, while formaldehyde emissions are similar. There is contradictory information about the emissions of acetaldehyde tailpipe emissions with some studies showing and increase while other show a decrease compared with petrol. More research is required to clarify this issue.

14.6 OHS Issues

Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and is a moderate irritant. The flash point of the fuel emulsion becomes that of alcohol when the alcohol content exceeds 5% of the volume.

Ethanol fuels increase permeation of elastomers that have been used in automotive applications (eg: rubber hoses, plastic fuels tanks). Research is required to quantify the permeation impacts of ethanol. (Harold Haskew & Associates, 2001).

The OHS issues in the lifecycle of ethanol are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with ethanol based fuels compared with LSD, no OHS issues unique to the production and distribution of ethanol have been identified.

14.7 Vapour Pressure Issues

There is contradictory information about evaporative emissions from ethanol added fuels. Some studies indicate that the use of ethanol results in substantial reductions in refuelling vapours. Others state that to contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure, and control evaporative emissions from diesel fuel vehicles.

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[1] Carnegie Mellon University Equivalent Toxicity

The higher vapour pressure of ethanol/gasoline blends compared to neat gasoline is a concern in their use. The effects of ethanol addition to PULP do not appear to have been specifically studied, but other studies with ethanol/gasoline blends provide useful guides to the magnitude of the effects.

Effects of ethanol addition on Reid vapour pressure have been summarised in a National Research Council report (NRC, 1999) produced for the USEPA, as follows:

> Studies indicate that fuel RVP increases as ethanol is initially added. The greatest RVP increase occurs with an ethanol content of about 5 vol % and is about 1 psi (~ 6.9 kPa). For ethanol concentrations greater than 5 vol %, the RVP slowly decreases

There are comprehensive studies of ethanol blends (CARB, 1998), which show that adding 10% ethanol to gasoline, resulting in an increase of RVP from 48 kPa to 55 kPa, increases the evaporative hydrocarbon emissions by an estimated 40%. The impacts of these increases on ozone-forming potential are discussed below.

Evaporative emission system technologies designed to reduce evaporative emissions from vehicles using gasoline and gasoline blended with 10 percent ethanol have also been examined (Louis Browning of ARCADIS Geraghty & Miller, reported in CRC (1999)). When using ethanol in gasoline, evaporative emissions are almost twice as high as when using gasoline without ethanol due to much higher permeation rates. This study also showed that by using low permeation materials, evaporative emissions could be substantially reduced from both fuels.

Effects of ethanol blends on ozone forming potential

CARB (1998) report overall increases of 40% in evaporative emissions in a 10% ethanol/gasoline blend using multi-day test procedures. As a consequence of this increase in evaporative emissions CARB estimate that use of a 10% ethanol blend would result in an overall increase of about 17% in ozone forming potential for the ethanol blend compared to a fully complying (RVP less than 7 psi or 48 kPa) gasoline. On this basis they have recommended against the use of 10% ethanol blends.

Similarly the NRC (1999) concludes that the use of an ethanol-containing fuel with a 1 psi higher RVP is likely to produce a negative air quality impact.

By contrast, the USEPA have recently (USEPA, 2000) proposed an adjustment to the reformulated gasoline VOC standard to encourage the use of ethanol blends given the beneficial impacts of ethanol on CO emissions in particular. It should be noted, however, that this increased use is associated with strict controls on the volatility of the gasoline with which the ethanol is blended, and hence requires changes to refinery practice and co-operation between refiners and ethanol manufacturers.

In any case evaporative emissions are a critical issue in the use of ethanol blends, and need to be evaluated with direct reference to Australian conditions, including emissions performance of the Australian fleet and current refinery practice.

14.8 Environmental Issues

Environmental and ESD issues associated with ethanol are discussed in Chapter 6.

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid.

The tailpipe greenhouse gas emissions from petrohol (from renewable sources) are lower than those of petrol because of the use of a renewable fuel in the blend, but this advantage is offset by reduced fuel economy. On a life-cycle basis the source of the ethanol is crucial in determining whether it is, or is not, climate friendly. Only petrohol made from wood waste has lower exbodied greenhouse gas emissions than premium unleaded petrol. Provided that ethylene is not used as the feedstock, then the exbodied emissions of air toxics are lower from petrohol than from petrol. The increased evaporative emissions from petrohol indicate the possibility of increased emissions of ozone pre-cursors.

14.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 14.11 lists the estimated emissions factors for oxygenated petrol. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of petrohol. The estimates of Arcoumanis (2000) indicate that petrohol can be expected to meet all future Australian Design Rules for all pollutants.

Table 14.11
Estimated emission factors for petrohol under future technologies (PM is unregulated)

Technology	**CO**	**CO**	**THC**	**THC**	**NOx**	**NOx**	**CO_2**	**LCA CO_2**
Euro2	**1.0**	0.9	**1.0**	0.9	**1.0**	1.0	**1.0**	0.9
Euro3	**1.05**	0.6	**0.59**	0.5	**0.6**	0.6	**1.0**	0.85
Euro4	**0.45**	0.3	**0.29**	0.3	**0.32**	0.3	**1.0**	0.8

14.10 Summary

14.10.1 Advantages

- As a renewable fuel it should produce less fossil CO_2 than conventional fuels, but the decrease in energy content of the ethanol means that more fuel has to be burnt. This increased fuel consumption, combined with the greater processing energy of the ethanol, means that exbodied greenhouse gases generally increase (albeit very slightly), the only exception being the case of ethanol made from wood waste.
- Tailpipe emissions of CO and HC appear to be lower on average.
- Air toxic levels decrease as the ethanol concentration increases.

14.10.2 Disadvantages

- There are high hydrocarbon evaporative emissions that require adjustment of the vapour pressure of the base petrol to which ethanol is added.
- There are problems of phase stability in the petrol mixture if water is present.

15. Hydrogen

15.1 Introduction

Cars, trucks and buses can burn pure hydrogen in an internal combustion engine, or use it in a fuel cell to drive an electric motor. The fuel cell option is generally considered preferable for the long term, because although it requires more changes to existing vehicle design, it allows for higher efficiency and hence a longer range on the same amount of fuel. This section will thus consider the upstream emissions associated with producing hydrogen of the purity required for fuel cells.

Hydrogen is the chemical element with the smallest molecular mass. Hydrogen is not found as a free element on earth. Because of its high reactivity, it is always bonded to other molecules. As a result hydrogen for automotive use has to be man made.

The hydrogen energy content per unit mass is high. Compared to petrol for example, it is three times as high. On a volume basis, the energy content of hydrogen is relatively small. Both properties can be found in Table 15.1

Table 15.1
Physical properties of hydrogen

	Lower calorific value Mass basis (MJ/kg)	Lower calorific value Volume basis (MJ/L)
Hydrogen	119.9	8.9*
Petrol	41.2	31.0
Diesel oil	42.9	36.1

* Liquid hydrogen at -253ºC

Gaseous hydrogen is very light (90 grams per cubic metre [g/Nm^{-3}]) at ambient conditions and rises in air. Burning hydrogen rises in air as well. This is in contrast to burning petrol, for example, which stays at ground level.

All mixtures of hydrogen and air with a volumetric hydrogen content between 4% and 75% are inflammable. Compared to mixtures of petrol and air, this is a wide range. Hydrogen can burn in mixtures with air from very lean (excessive air) to rich (excessive fuel). The ignition energy is very low, so the combustion process can be initiated easily. The flame propagation speed of burning hydrogen is high. In an experimental spark ignited engine with direct gaseous hydrogen injection, flame speeds up to 40 m/s have been measured, at various engine speeds. The flame speeds obtained with internal mixture formation were significantly higher than those with external mixture formation (Meier et al., 1994). These high flame speeds necessitate engine adaptation.

The important safety aspects for handling hydrogen are discussed in the next section.

15.2 Full Fuel-Cycle Analysis

15.2.1 Tailpipe

We consider only fuel-cell powered vehicles. Such hydrogen vehicles have virtually no emissions, even of NOx, because fuel cells operate at temperatures that are so much lower than internal combustion engines that NOx is not formed from the nitrogen and oxygen in the air. Theoretically, a hydrogen-fuelled fuel cell vehicle emits only water vapour.

DaimlerChrysler in Europe established a subsidiary, EvoBus GmbH to fit a limited number of vehicles with the latest generation of fuel cells and use them in buses being used for public transport.

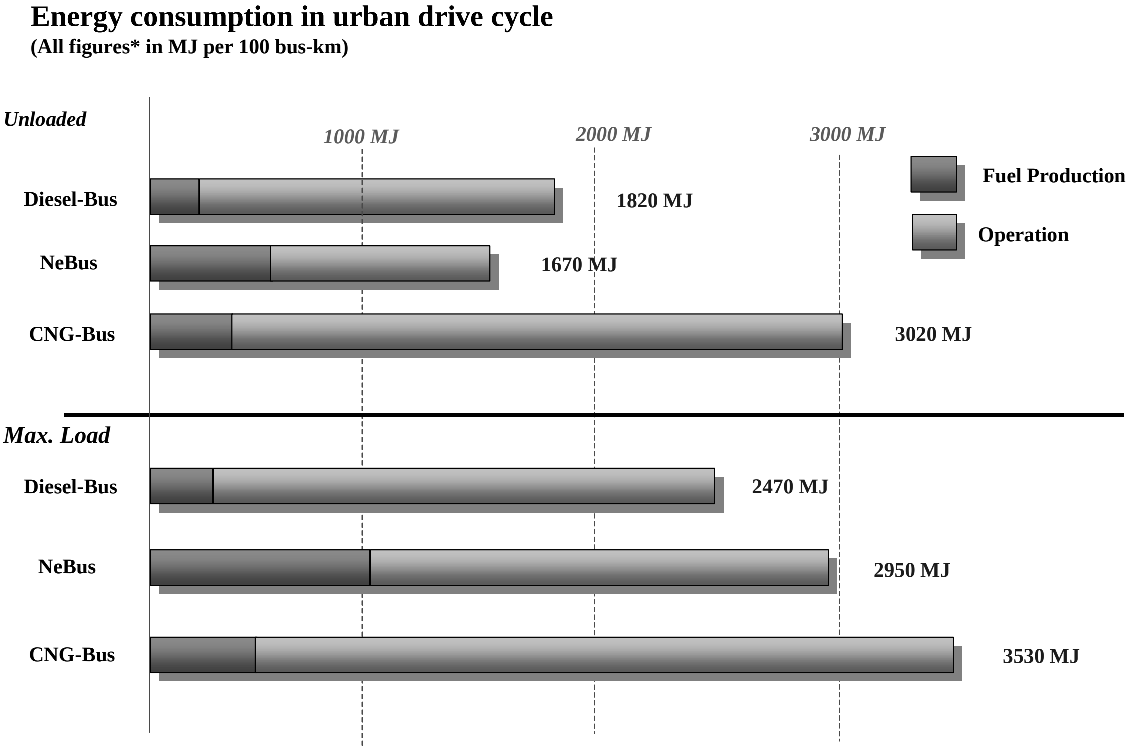


Figure 15.1
Energy consumption in urban drive cycle for buses (Graham, 2000)

During March 2000, a hydrogen fuel cell bus (NeBus) was exhibited in Perth and Melbourne. Figure 15.1 reproduces the energy consumption for the NeBus along with some comparative energy consumption (Graham, 2000). During operation, though energy is being used, this study will assume that the tailpipe emissions are purely water vapour.

Following on from these demonstrations, Perth will operate three fuel cell buses by late 2002. BP will invest more than $1 million in Western Australia to establish a hydrogen manufacture and supply chain. A small purification unit at the BP Kwinana refinery will produce the requisite high quality hydrogen for the buses.

15.2.2 Upstream

Production of Hydrogen

Hydrogen can be produced through steam reforming of natural gas, cleanup of industrial by-product gases, or electrolysis of water. This section will consider only steam reforming of natural gas.

The main commercial processes specific for the manufacture of hydrogen are steam reforming of natural gas or other hydrocarbons, coal gasification, and water electrolysis. Relatively small quantities of hydrogen are produced by steam reforming of naphtha and partial oxidation of natural gas. Oil refineries also recover hydrogen from some of their process units, most commonly from reformers.

Overall, the main chemical reactions used in these processes are as follows :

Steam reforming	$CH_4 + 2H_2O = CO_2 + 4H_2$
Naphtha reforming	$C_nH_{2n} + 2n\ H_2O = nCO_2 + 3nH_2$
Partial oxidation	$CH_4 + O_2 = CO_2 + 2H_2$
Coal gasification	$C + 2H_2O = CO_2 + 2H_2$
Water electrolysis	$2H_2O = 2H_2 + O_2$

Worldwide, hydrogen as a raw material for the chemical industry is produced predominantly from natural gas (about 70%), with other petroleum feedstocks, coal, and water electrolysis accounting for the remainder. Process steps involved in natural gas reforming are illustrated in Figure 15.2.

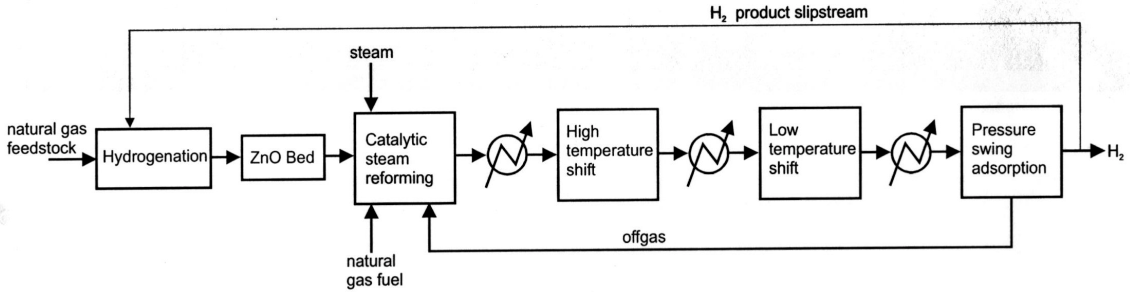


Figure 15.2
Diagram of the process for hydrogen production from natural gas incorporating PSA purification (from Spath and Mann, 2001).

In steam reforming, hydrocarbons contained in natural gas (mostly methane) are converted to synthesis gas (mixture of H_2, CO, CO_2) by reaction with steam over a catalyst in a primary reformer furnace. This process is usually operated at 800–870°C and 2.2–2.9 MPa, using a Ni-based catalyst.

Because hydrocarbon feeds for steam reforming should be free of sulfur, feed desulfurisation is required ahead of the steam reformer. The desulfurisation step usually consists of passing the sulfur-containing natural gas feed at about 300–400°C over a CoMo catalyst in the presence of 2–5% H_2 to convert organic sulfur compounds to H_2S.

This is then followed by adsorption of H_2S over a ZnO guard bed to reduce the sulfur level to less than 0.1 ppmwt which is the level that the reforming catalyst can tolerate.

The gas and process steam mixture is then introduced into the primary reformer. This reformer is a direct natural gas fired chamber containing rows of nickel-alloy tubes filled with the catalyst pellets. The gas leaving the primary reformer is about 76.7% H_2, 12% CO, 10% CO_2, and 1.3% CH_4. Up to 95% conversion of CH_4 can be achieved in the primary reformer.

In the next step, the CO is converted to CO_2 and hydrogen by the water gas shift (WGS) reaction step:

Water gas shift reaction $CO + H_2O = H_2 + CO_2$

The combination of this reaction with those occurring in the reformer gives the overall reaction stoichiometry presented earlier.

This reaction is first conducted on a chromium-promoted iron oxide catalyst in the high temperature shift (HTS) reactor at about 370°C at the inlet. Converted gases are cooled outside of the HTS and are sent to the low temperature shift (LTS) converter at about 200–215°C to complete the water gas shift reaction. The LTS catalyst is a copper–zinc oxide catalyst supported on alumina. The product gas after WGS contains about 77% H_2, 18% CO_2, 0.30% CO, and 4.7% CH_4.

The gas is then cooled and CO_2 scrubbed out by hot potassium carbonate or other processes such as MEA, methyldiethanolamine (MDEA) or other similar technology. The scrubbed gas contains about 98.2% H_2, 0.3% CO, 0.01% CO_2, and 1.5% CH_4.

Remaining carbon oxides are converted to methane by passing the gases reheated to about 315°C over a methanation catalyst, usually containing about 35% Ni supported on refractory material. Over this catalyst, CO and CO_2 are hydrogenated to CH_4. A typical hydrogen product is 98% H_2 and 2% CH_4.

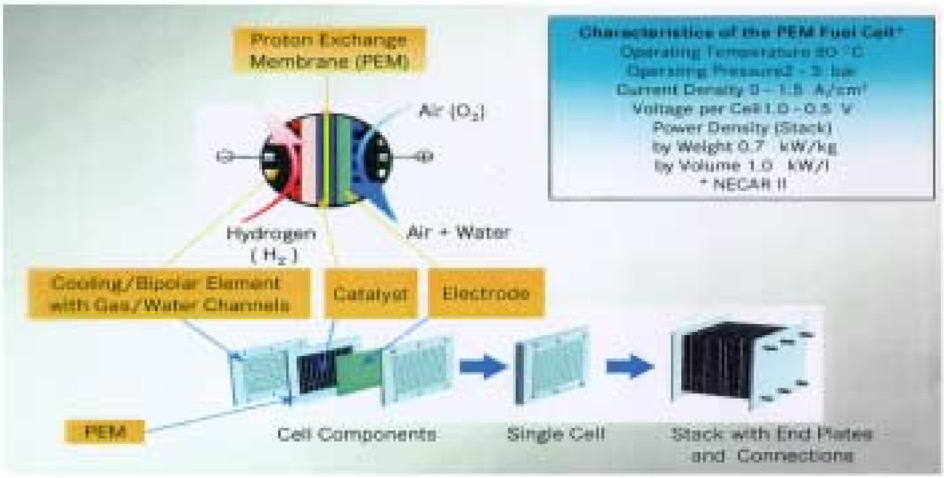
As an alternative to scrubbing out the CO_2 followed by methanation, the shifted gas can be purified by pressure-swing adsorption (PSA) when high purity hydrogen is desirable. PSA is used in nearly all cases where high purity (>99%) hydrogen is needed. Pressure-swing adsorption utilizes the fact that larger molecules such as CO, CO_2 and CH_4 can be separated from the smaller hydrogen gas molecule by selective adsorption on high surface area materials such as molecular sieves. Hydrogen has a very weak affinity for adsorption. The process of pressure-swing adsorption is capable of producing very pure (>99.9%) hydrogen at recoveries of 70–90%, depending on the number of adsorption stages.

In applications where an ultra-pure hydrogen is required, for example in proton exchange membrane (PEM) fuel cells used in vehicles, final purification may be achieved by using palladium membranes. This process utilises the fact that hydrogen diffuses through palladium metal at high temperatures (about 600^{o}C).

Upstream emissions in hydrogen production arise from natural gas recovery and purification, heat requirements of the steam reformer and energy demand of all process units. Further emissions arise from the chemistry of the process as illustrated by chemical equations. In a sense, hydrogen production can be seen as “decarbonisation” of natural gas, with all carbon converted into carbon dioxide.

Spath and Mann (2001) recently revised their earlier calculations in relation to the life cycle assessment of hydrogen production from natural gas steam reforming. Their updated estimates have been used in the quantitative parts of the life-cycle calculations.

Use



The fuel cell works by bringing about a controlled reaction between hydrogen and oxygen. The hydrogen passes through the fuel cell's electrolyte in the form of positively charged ions (protons). It then combines with oxygen in the air to form water leaving behind negatively charged electrons. As a negative charge accumulates on one side of the electrolyte and a positive charge on the other, an electric voltage is generated, which is then converted and drives the vehicle via the electric wheelhub motors.

Figure 15.3
Proton exchange membrane fuel cell (source: DaimlerChrysler)

Figure 15.3 depicts the details of a PEM fuel cell. Because fuel cell vehicles are in a very early state of development, it is difficult to predict what the energy consumption of this type of vehicles will be in a mature situation. However, some indications can be given. From previous research it was found that the energy efficiency of a fuel cell vehicle without regenerative breaking is 42 - 48%, from vehicle tank to wheels. For fuel cell vehicles with regenerative braking, this figure is 46-55% (van Walwijk et al., 1996). These figures are supported by a recent publication of Mercedes Benz. For a concept fuel cell van (rolling laboratory type), a part load efficiency of 40% is reported (van Walwijk et al., 1996).

15.3 Results

15.3.1 Emissions per unit energy

Table 15.2
Exbodied emissions (per MJ) for hydrogen (from natural gas)

Full Lifecycle	Units	LS diesel	Hydrogen (from natural gas)
Greenhouse	kg CO_2	0.0834	0.0832
HC total	g HC	0.138	0.033
HC urban	g HC	0.110	0.001
NOx total	g NOx	1.016	0.053
NOx urban	g NOx	0.986	0.035
CO total	g CO	0.249	0.012
CO urban	g CO	0.240	0.005
PM10 total	mg PM10	39.7	0.7
PM10 urban	mg PM10	39.3	0.4
Energy embodied	MJ LHV	1.16	1.41

Table15.3
Precombustion emissions (per MJ) for hydrogen (from natural gas)

Precombustion	Units	LS diesel	Hydrogen (from natural gas)
Greenhouse	kg CO_2	0.0167	0.0832
HC total	g HC	0.0548	0.0332
HC urban	g HC	0.126	0.001
NOx total	g NOx	0.073	0.053
NOx urban	g NOx	0.043	0.035
CO total	g CO	0.019	0.012
CO urban	g CO	0.010	0.005
PM10 total	mg PM10	4.4	0.676
PM10 urban	mg PM10	4	0.435
Energy embodied	MJ LHV	1.16	1.41

Table 15.4
Summary of exbodied emissions from hydrogen

		LS diesel	Hydrogen (from natural gas)
Greenhouse kg	Precombustion	0.0167	0.0832
Greenhouse kg	Combustion	0.0667	0.0000
HC total g	Precombustion	0.0548	0.0332
HC total g	Combustion	0.0835	0.0000
HC urban g	Precombustion	0.1262	0.0011
HC urban g	Combustion	0.0835	0.0000
NOx total g	Precombustion	0.0726	0.0527
NOx total g	Combustion	0.944	0.000
NOx urban g	Precombustion	0.043	0.035
NOx urban g	Combustion	0.944	0.000
CO total g	Precombustion	0.0191	0.0121
CO total g	Combustion	0.2301	0.0000
CO urban g	Precombustion	0.0096	0.0046
CO urban g	Combustion	0.2301	0.0000
PM10 total mg	Precombustion	4.40	0.68
PM10 total mg	Combustion	35.26	0.00
PM10 urban mg	Precombustion	4.00	0.44
PM10 urban mg	Combustion	35.26	0.00
Energy embodied MJ	Precombustion	1.16	1.41
Energy embodied MJ	Combustion	0	0

15.3.2 Emissions per unit distance

Table 15.5
Exbodied emissions (per km) for hydrogen (from natural gas)

Full Lifecycle	Units	LS diesel	Hydrogen (from natural gas)
Greenhouse	kg CO_2	0.9250	0.8970
HC total	g HC	1.509	0.358
HC urban	g HC	1.192	0.012
NOx total	g NOx	11.250	0.568
NOx urban	g NOx	10.638	0.372
CO total	g CO	2.723	0.131
CO urban	g CO	2.612	0.049
PM10 total	mg PM10	438.4	7.3
PM10 urban	mg PM10	423.1	4.7
Energy embodied	MJ LHV	12.7	15.2

Table 15.6
Precombustion emissions (per km) for hydrogen (from natural gas)

Precombustion	Units	LS diesel	Hydrogen (from natural gas)
Greenhouse	kg CO_2	0.2060	0.8970
HC total	g HC	0.609	0.358
HC urban	g HC	0.292	0.012
NOx total	g NOx	1.080	0.568
NOx urban	g NOx	0.468	0.372
CO total	g CO	0.243	0.131
CO urban	g CO	0.132	0.049
PM10 total	mg PM10	58.4	7.28
PM10 urban	mg PM10	43.1	4.68
Energy embodied	MJ LHV	12.7	15.2

Table 15.7
Exbodied emissions summary (per km) for hydrogen (from natural gas)

		LS diesel	Hydrogen (from natural gas)
Greenhouse kg	Precombustion	0.2060	0.8970
Greenhouse kg	Combustion	0.7190	0.0000
HC total g	Precombustion	0.6090	0.3580
HC total g	Combustion	0.9000	0.0000
HC urban g	Precombustion	0.2920	0.0120
HC urban g	Combustion	0.9000	0.0000
NOx total g	Precombustion	1.0800	0.5680
NOx total g	Combustion	10.170	0.000
NOx urban g	Precombustion	0.468	0.372
NOx urban g	Combustion	10.170	0.000
CO total g	Precombustion	0.2430	0.1310
CO total g	Combustion	2.4800	0.0000
CO urban g	Precombustion	0.1320	0.0492
CO urban g	Combustion	2.4800	0.0000
PM10 total mg	Precombustion	58.40	7.28
PM10 total mg	Combustion	380.00	0.00
PM10 urban mg	Precombustion	43.10	4.68
PM10 urban mg	Combustion	380.00	0.00
Energy embodied MJ	Precombustion	12.70	15.20
Energy embodied MJ	Combustion	0	0

There is insufficient information with which to estimate quantitatively the uncertainties associated with the use of hydrogen as a fuel.

15.4 Viability and Functionality

Important advantages of fuel cells are: high energy efficiency, because the efficiency is not limited to the maximum efficiency of thermal energy processes; low emissions during operation, though manufacturing of fuel cells may cause emissions; and low noise production.

However, fuel cells have some disadvantages as well. Compared to internal combustion engines, the disadvantages are: fuel cells are very expensive; and fuel cells are large and heavy per kW output. Most research concentrates on reducing these disadvantages.

Three different methods for on-board hydrogen storage have been considered (van Walwijk et al., 1996):

- high pressure hydrogen gas
- hydride, where hydrogen is chemically bound to a metallic material
- cryogenic storage of liquid hydrogen, at low temperature.

The storage method used for the NeBus is shown in Figure 15.4.

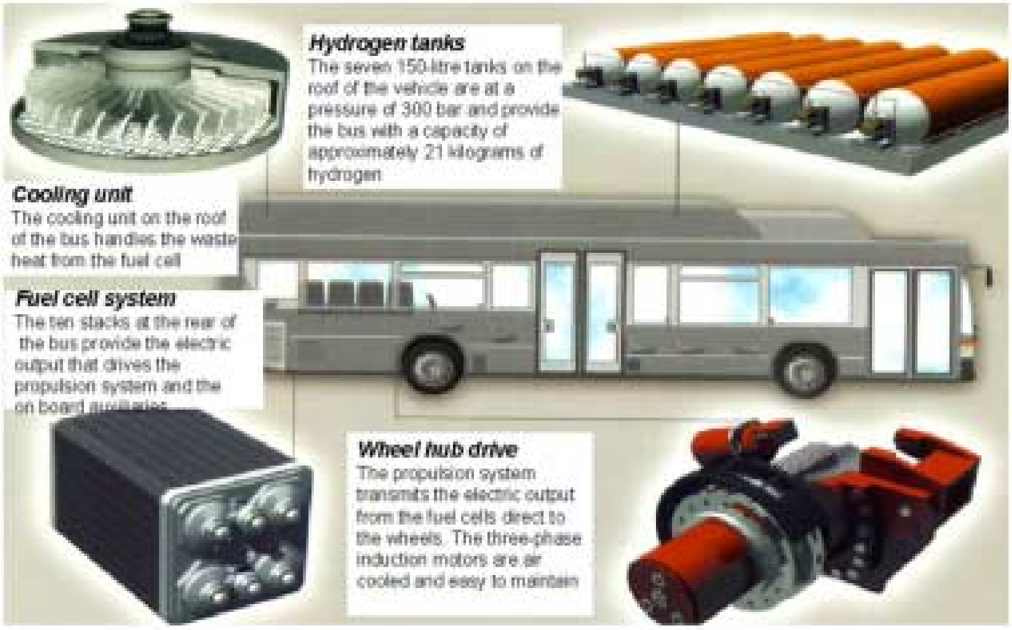


Figure 15.4
Storage method for the NeBus hydrogen bus

15.4.1 Safety

Safety is an important issue regarding hydrogen production, transport and use in a vehicle (refuelling, on-board storage and in case of collisions). In this section, safety aspects of hydrogen when used as fuel for road vehicles are discussed. First, the circumstances in which hydrogen can be dangerous and the reasons for this, are discussed.

Hydrogen rises when it is released into the open air. Its safety is then similar to that of conventional fuels. However, in closed rooms, hydrogen is more dangerous than conventional fuels. Hydrogen can burn in mixtures with air from very lean - with excess air - to very rich .

The flame propagation speed is very high, which gives the combustion an explosive character. A spark from a light switch can start the combustion process for example. A (local) pressure peak can also ignite hydrogen-air mixtures. These pressure peaks are not found in the open air but may occur in closed rooms at locations where different pressure waves interfere.

Two notorious accidents contributed to the general concern regarding the safety of hydrogen. In 1937, the ‘Hindenburg’ airship burnt down in a few seconds, and in 1990 a Space Shuttle exploded just after take-off. Both had hydrogen on-board. At the accident with the ‘Hindenburg’ relatively few spectators were hurt because the burning hydrogen rose in the air. Because of the high flame propagation speed, an accidental hydrogen fire never lasts long.

Refuelling of hydrogen vehicles is discussed later. To avoid explosions, evaporating hydrogen is extracted during the refuelling process. For example, BMW has developed a fully automatic refuelling system which may be safely used by anyone. For on-board storage of hydrogen, some hydrogen has to be vented when a hydrogen vehicle is not used over a longer period of time, because the fuel tank cannot be 100% isolated. A safety valve in the vehicle tank prevents excessive tank pressures. Sensors inside the vehicle can detect hydrogen and the vehicle windows can be opened automatically if so required. Evaporative hydrogen losses will also occur when the vehicle is parked in a garage. To avoid ignitable mixtures of hydrogen in air, four different measures can be taken:

- Hydrogen can be exhausted by a spark free venting system
- A small fuel cell can be mounted in the vehicle. Evaporating hydrogen can then be used in this fuel cell to generate electricity, which can be stored in the vehicle batteries to be used later. This type of fuel cell has not been developed yet.
- Evaporated hydrogen can be stored in a metallic hydride, in which it is chemically bound to a metallic material. More information on hydride storage can be found in section 12.5. It has to be kept in mind that heat is generated when hydrogen is being stored in a metallic hydride.
- When the hydrogen vehicle is equipped with a fuel cell instead of a combustion engine, the fuel cell can be used to convert the evaporated hydrogen automatically into electrical energy which may be stored in the batteries.

The safety of hydrogen fuel systems is important during vehicle collisions. There is substantial testing designed to ensure leakproof hydride tanks, and to place the vehicle tank inside the safety cage of vehicles so as to reduce the risk of damage to the tank during a collision.

Van Walwijk et al. (1996) report that accidents with hydrogen vehicles are no worse than those with LPG or natural gas. However, they also point out that no results from collision tests with hydrogen vehicles could be found in the literature.

15.4.2 Warranty

Hydrogen powered vehicles are supplied by the engine manufacturer.

15.4.3 Functionality of the fuel under the full range of Australian conditions

There is no reason to expect any lack of functionality of hydrogen under Australian conditions.

15.4.4 Fuel energy density and vehicle operational range

The driving ranges of comparable diesel and hydrogen vehicles are different, when the mass of fuel tank and fuel are the same. It is smaller for hydrogen vehicles. The diesel vehicle can drive twice the distance. The specifications for the DaimlerChrysler NeBus specify 7 roof-mounted pressure resistant cylinders (weighing 1,900 kg) to give a range of 250 km, with a passenger capacity of 34 seated and 24 standing (58 passengers). These figures are similar in range to earlier generation CNG buses and compare to a typical range of 400 km for an equivalent diesel bus (Cannon and Sun, 2000).

BMW has been working on liquid storage systems. Mass and storage volume are acceptable. A disadvantage is the storage temperature of -253ºC for liquid hydrogen, which requires an insulated vehicle tank. In a vehicle, the storage tank is not refrigerated. This results in evaporative losses when the engine is not running. Due to the unavoidable leaking of heat to the storage tank, some hydrogen will evaporate. This gas must be able to escape (or must be used) to avoid excessive pressures and to maintain a low temperature in the vehicle tank. The fact that the energy of the heat is used as evaporation energy helps to maintain a low temperature in the vehicle as well. With appropriate insulation and a tank pressure of 5 bar, it is possible to avoid venting for three or four days. After that period, the evaporative losses continue.

15.4.5 Refuelling requirements

To refill a hydrogen vehicle, an onward (for liquid hydrogen) and a return (for gaseous hydrogen from the vehicle tank) hose are connected to avoid losses of hydrogen during refuelling. BMW has developed a refuelling system in which, after connecting the hoses to the vehicle, the complete system - including the vehicle part - is flushed with helium before the refuelling commences. This is to avoid ignitable mixtures of hydrogen and air. After the system has been flushed, the refuelling of the vehicle may commence.

Most hydrogen vehicles are being refuelled with liquid hydrogen. When refuelling a cold hydrogen tank with liquid hydrogen, approximately 10% of the hydrogen will become gaseous upon entering the tank. For warm vehicles, the percentage can increase up to 25%. These evaporative losses are being exhausted back to the storage tank of the refuelling station. In this way losses of hydrogen can be avoided, including the loss of energy, which is directly related to a loss of hydrogen.

Refuelling time of vehicles with a tank for liquid hydrogen at (-253ºC) is between three and ten minutes, when the vehicle tank is cold. However, an empty vehicle tank will slowly warm up to ambient temperature. Refuelling of a tank that is at ambient temperature has to be done relatively slowly. The refuelling time of a hydrogen vehicle can thus rise to ten times the refuelling time of a petrol vehicle.

Refuelling time of hydrogen vehicles with metallic hydride storage tanks is lengthy compared to conventionally fuelled vehicles. Heat is generated when the hydrogen is bound to the metallic hydride. This heat has to be removed during the refuelling process.

15.5 Health Issues

There are no air pollutant or greenhouse gas emissions during operation. The only emissions that may be of concern arise during precombustion.

15.5.1 Production and transport

Upstream emissions in hydrogen production arise from natural gas recovery and purification, heat requirements of the steam reformer and energy demand of all process units. Further emissions arise from the chemistry of the process.

Particulate matter

The LCA estimate for hydrogen urban precombustion (truck) PM10 emissions of 5 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for hydrogen urban precombustion (truck) HC emissions of 0.012 g/km is substantially less than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

15.5.2 Use

We consider only fuel-cell powered vehicles. Such hydrogen vehicles have virtually no emissions, even of NOx, because fuel cells operate at temperatures that are so much lower than internal combustion engines that NOx is not formed from the nitrogen and oxygen in the air. Theoretically, a hydrogen fuelled fuel cell vehicle emits only water vapour.

Particulate matter

The LCA estimate for hydrogen combustion (truck) PM10 emissions of 0 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air toxics

The LCA estimate for hydrogen combustion (truck) HC emissions of 0 g/km is substantially less than the LSD estimate of 0.900 g/km.

15.5.3 Summary

Hydrogen upstream emissions of both particles and HC are substantially less than LSD. Hydrogen has no tailpipe emissions of particles or air toxics.

15.6 OHS Issues

There are a range of OHS issues that must be considered when handling hydrogen.

Safety is an important issue regarding hydrogen production, transport and use in a vehicle (refuelling, on-board storage and in case of collisions). Hydrogen rises when it is released into the open air. Its safety is then similar to that of conventional fuels. However, in closed rooms, hydrogen is more dangerous than conventional fuels. Hydrogen can burn in mixtures with air from very lean - with excess air - to very rich. The flame propagation speed is very high, which gives the combustion an explosive character. A spark from a light switch can start the combustion process for example. A (local) pressure peak can also ignite hydrogen-air mixtures. These pressure peaks are not found in the open air but may occur in closed rooms at locations where different pressure waves interfere.

Safety is also an important issue for on-board storage of hydrogen. It has already been discussed in the section on viability and functionality.

15.7 Vapour Pressure Issues

Most hydrogen vehicles are being refuelled with liquid hydrogen. Evaporative losses during refuelling can be exhausted back to the storage tank of the refuelling station. In this way losses of hydrogen can be avoided, including the loss of energy, which is directly related to a loss of hydrogen.

15.8 Environmental Impact and Benefits

Hydrogen is a gaseous fuel with no air pollutant or greenhouse gas emissions. It thus cannot contaminate soil or water. Provided that an environmentally sustainable system can be produced then the use of hydrogen would be highly beneficial. Manins (1992) proposed an innovative scheme based on using tidal power to dissociate hydrogen and thus run a hydrogen economy. The theoretical potential is great for environmental benefits provided the technology can be implemented.

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1. Weighting Methodologies for Emissions from Transport Fuels

1.1 Introduction

1.1.1 *Scope of Work*

This chapter responds to a request from the Australian Greenhouse Office (AGO) to develop a weighting scheme for air quality that enables all emissions affecting air quality to be weighted and combined into a single measure of air quality. The international agreement on the use of the GWP as a weighting factor for different greenhouse gases means that it is straightforward to calculate the greenhouse gas emissions in CO_2-equivalents, and this measure can be used to compare the greenhouse gas emissions performance of different alternative fuels. There is no similar agreement in relation to other gases that fall under the general category of air pollutants.

The chapter explores alternative approaches to address the question of how to weight emissions that affect air quality. A range of models are presented that should only be considered as being illustrative of possible approaches and how they would be implemented. In section 1.4 and 1.5, the purpose of examining these models is to promote discussion about possible models and methodologies for weighting fuels, rather than a debate about the merits of each fuel.

No conclusions are meant to be drawn from the analysis of the fuels themselves in sections 1.4 and 1.5. Another approach might have been to refer to fuels “A”, “B” and “C” rather than specific fuels. However, this approach might have been considered to be too abstract. In summary, each example should be examined in terms of the merits of the model and the methodology by which it weights emissions rather than the outcome for each fuel.

Section 1.6 applies a weighting methodology as specified by Environment Australia.

1.2 Background

The air that we breathe is a mixture of many different gases. It is a mixture of 78% nitrogen, 21% oxygen, slightly under 1% argon, and about 0.037% carbon dioxide. These percentages are based on units for the gases that comprise volume mixing ratios.

We can represent such a mixture mathematically. In this case:

$$A = \Sigma w_i E_i \qquad (1)$$

where A represents air, w represents the proportions of each gas (0.78, 0.21, 0.00963, 0.00037), and E is the volume mixing ratio of each of the gases. The symbol Σ represents summation, in this case over four gases.

This simple example illustrates the difficulties that are involved in any weighting scheme. Firstly, there needs to be a decision on the choice of weights (w in this case). Secondly, there needs to be a decision as to the appropriate units for the gases (percentages by volume, in this case). Thirdly, there needs to be a decision on the number of entities to be summed.

The example given above, for air, is straightforward because its composition can be determined by direct experiment. There is another straightforward example, namely that of greenhouse gases. International agreement has been reached on how to combine greenhouse gases. Before proceeding to the more difficult case of air quality weighting schemes, the weightings used for greenhouse gases will be reviewed.

1.3 Greenhouse Gases

The Australian National Greenhouse Gas Inventory (NGGIC, 2000) follows the international agreement that Greenhouse gas emissions will be weighted using IPCC 100 year global warming potentials as given in Table 1.1.

Table 1.1
100 years global warming potentials

Gas	GWP
Carbon dioxide	1
Methane	21
Nitrous Oxide	310
Sulfur Hexafluoride	23900
CFC-11	3800*
CF_4	6500
C_2F_6	9200

*Direct only. Other estimates include indirect effects

This means that a measure of greenhouse gases, called the carbon dioxide equivalent (CO_2-e), is computed as:

$$CO_2\text{-e} = CO_2 + 21\ CH_4 + 310\ N_2O + 23900\ SF_6 + \ldots \qquad (2)$$

where the weights are as given in Table 1.1, and the gases are measured in units of mass per unit time, tonnes per year being a representative example.

1.4 Air Quality

There is no agreement on how to combine air pollutants. This section reviews existing available weighting methodologies.

1.4.1 Air quality indexes

Air pollution control authorities have found it useful, when presenting air quality information to the public, to use an Air Quality Index — or an Air Pollution Index — as a means of combining information on all of the pollutants.

Table 1.2
Victorian air pollution index categories

Air quality category	Associated colour	Index range
Very Good	Blue	0-33
Good	Green	34-66
Fair	Yellow	67-99
Poor	Red	100-149
Very Poor	Black	150 or higher

(Source: http://www.epa.vic.gov.au/aq/abindex.htm)

Australian authorities typically use the ratio of pollutant concentration to pollutant standard level as the basis from which to construct an air quality index. Victoria, for example, expresses the index value as a percentage that is calculated for ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, fine particles (PM10) and visibility. The maximum of these figures is taken as the index value for the relevant monitoring station, and one of five colour-coded air quality categories (from blue to black) is chosen on the basis of the index, as shown in Table 1.2.

In this case the weights, w, are given by

$$w = 100/(\text{value of the NEPM standard}) \qquad (3)$$

so that the measure of the pollutant, E, need to be expressed in the same units as the NEPM standard. Air pollution indexes in Australia are not based on a sum of weighted pollutants, unlike Equation (1), but are set equal to the maximum value of the weighted pollutants.

1.4.2 Stage 1 Alternative Fuels Study Method

The Stage 1 alternative fuels study (Beer et al., 2000) developed a weighting scheme to rank various alternative fuels. The scheme was based on two major criteria:

1. Health effects guided the choice of the weights, *w.*
2. The quantities being evaluated (E) were the **ranked score** for the pollutant.

Emissions of carbon monoxide do not cause problems in Australia, so that the study believed that it did not need to be considered in evaluating alternative fuels. NOx and NMHC (i.e. THC less methane) together are important because they are the precursors of smog. . NOx (in the form of NO_2) is linked to respiratory illness. Particulate matter is of concern because of the epidemiological evidence that particulate matter has short-term and long-term health effects, including mortality, such that a 10 $\mu g/m^3$ increase in PM10 is associated with a 1% increase in mortality.

These air pollution and health considerations indicated that fuel emissions should be considered in two classes – those used primarily in urban areas (e.g. buses), and those used primarily in rural areas (e.g. trucks). Urban vehicles need to have low emissions of NOx, THC and particulate matter. However, as smog is not a problem in rural areas, the THC and NOx levels of emission are not as important as the particulate emissions. This is especially the case as the NEPM for Ambient Air Quality seeks equal protection for all Australians. Though it may be argued that rural particulate emissions are not important because of the occurrence of natural dust, there are theories that health effects arising from inhalation of particulate matter arise only when carbonaceous particles, such as those from combustion, are inhaled. Accordingly it was recommend in Beer et al. (2000) that rural and highway air quality evaluation include particles, particularly as many small country towns sit alongside major transport routes.

Ranking (including uncertainty)

The Stage 1 study ranked the emissions according to their average characteristics in terms of global warming and pollution impact, and assigned its rank value to each gas as a score.. To allow for variation in the emission results, the gases were ranked for one standard deviation above and below their average emissions and again scored. The three scores were summed, and the final ranking based on this sum.

This method is straightforward when calculating the rankings on the basis of greenhouse gases (expressed in CO_2-equivalents). In relation to air quality, the ranking was less straightforward. Because of the concern for human health and well-being, particulate matter is believed to pose the greatest health risk. Hydrocarbons pose a health risk in the long term, as a number of compounds are carcinogenic. In addition hydrocarbons are considered to be one of the precursors for the formation of ozone, and reductions in hydrocarbon are the most effective way of reducing ozone. Oxides of nitrogen are also ozone precursors, and NO_2 poses a health risk at high concentrations (which are rarely found in Australian cities). Finally, carbon monoxide poses a health risk at concentrations that do not occur in Australia.

It was thus decided to weight the air pollutants on the basis of their health risk.

Air pollution health risk

The NEPM for Ambient Air Quality (National Environment Protection Council, 1998) provides estimates of the short-term health effects of the criteria pollutants.

CO – Loss of 1 day's earning for 50,000 people at a cost of $6 million. (National Environment Protection Council, 1998: p.52)

NO_2 – 10 to 15% of the population display respiratory symptoms at a cost of $5 million. (National Environment Protection Council, 1998: p. 61)

O_3 – Up to 10 deaths per year in Australia, with total costs up to $810 million. (National Environment Protection Council, 1998: p.75-76)

PM - Up to 2,400 deaths per year in Australia, with an associated health cost of $17.2 billion. (National Environment Protection Council, 1998: pp.122 & 127)

In the absence of more detailed information, the health effects related to ozone (O_3) are ascribed equally to NOx and hydrocarbons. (National Environment Protection Council, 1998: p. 78)

In addition, hydrocarbons have long-term health effects that were examined by Hearn (1998) for Melbourne. If we extrapolate his figures to all of Australia then there are approximately 1250 to 1785 deaths per annum as a result of hydrocarbons (excluding deaths ascribed to the particulate matter in the hydrocarbons).

Insufficient is known about the source of the particulate matter to determine how much of it is attributable to traffic, and how much of the health effects are attributable to traffic. Industry emits particles, but these are generally in the larger size ranges. Present evidence indicates that most health effects result from the smaller sizes below PM10. Traffic emits most particles in the PM2.5 size range. Information on emissions alone does not provide insights into the contribution of traffic to airborne concentration of particles other pollutants will form secondary particulate matter. This report has examined particulate matter emissions as PM10.

The main health risk for Australians arises from particulate matter and from hydrocarbons. Given the considerable uncertainties associated with these estimates of mortality, and the costs of morbidity, the health risk weighted air quality rankings were as follows:

The summed score for particulate matter was multiplied by 2, the summed score for hydrocarbons was multiplied by 1, the summed score for NOx was multiplied by 0 (i.e it was ignored because less than 0.2% of health effects are related to NOx),, and the summed score for carbon monoxide was multiplied by 0 (i.e it was also ignored because less than 0.2% of health effects are related to CO),, and the totals added together to produce a final air quality score, as shown in Table 1.3.

Table 1.3
Fuel scores and final ranking in relation to air quality; the lowest value denotes the lowest emissions

Fuel	CityPM	CityHC	City NOx	CityAQ	CityAQ	Hwy PM	HwyHC	Hwy NOx	HwyAQ	HwyAQ
				Score	**Rank**				Score	**Rank**
Weight	2	1	0			2	1	0		
Diesel	28	25	24	81	**10**	14	17	17	45	**5**
LSD	15	15	20	45	**4**	16	10	15	42	**4**
LSD+W5	21	10	19	52	**5**	20	11	24	51	**7**
ULS	18	19	14	55	**7**					
ULS+W5	21	14	13	56	**8**					
LPG	9	4	4	22	**1**					
CNG	3	18	7	24	**2**	7	3	7	17	**1**
LNG	6	32	33	44	**3**	3	18	3	24	**2**
E95	15	24	7	54	**6**	8	24	8	40	**3**
BD20/35	29	17	30	75	**9**	16	14	20	46	**6**
BD100	33	20	27	86	**11**	24	11	14	59	**8**

1.4.3 Load-based licensing valuation methods

As a result of the NSW load-based licensing legislation, there has been substantial activity devoted to assigning the load valuation to be placed on airborne pollutants. The Environment Protection Authority (1997) produced a table of results, based on cost-benefit analyses of health effects, which are reproduced in Table 1.4. The pollutants are intended to deal with motor vehicle emissions. The dollar values are determined on the basis of the mean of valuations for US and European conditions.

Table 1.4
Valuation of airborne pollutants from motor vehicles (Environment Protection Authority, 1997)

Pollutant	Valuation ($/kg)
Particles	1.81
CO	0.025
NO_X	1.49
Total hydrocarbons (THC)	0.96

Thus, in some respects the valuation weighting method – being based on health risk weightings, agrees with the philosophy of the Stage 1 weighting method. It may be noted that when expressed in dollars per tonne, the numerical value for particles is approximately equal to the annual number of deaths in Australia attributed to particulate matter. With this in mind, some of the actual values appear curious. NOx, for example, appears to have a much higher value than one would expect on the basis of expected Australian health effects. However, applying the weights directly to mass emissions (rather than ranked scores) leads to a far more significant difference. To appreciate this difference, Table 1.5 has used the results of Beer et al. (2000: Table 3.1) to determine load valuations for tailpipe emissions of urban buses. Because of the combination of high NOx emissions (on a g/km basis) and a high NOx valuation, the resulting load valuation rankings are dominated by NOx.

Table 1.5
Load valuation (c/km) for tailpipe emissions from urban buses

Fuel	CO (g/km)	THC (g/km)	NOx (g/km)	PM (g/km)	c/km
Biodiesel	7.68	0.84	17.2	0.6	2.77
CNG	0.66	2.75	9.87	0.05	1.75
Diesel	1.88	1.1	15	0.47	2.43
E95	14.6	4.85	7.83	0.21	1.71
LNG	9.05	2.45	32.5	0.01	5.10

1.4.4 Index-based weighting (hazard-quotient method)

By analogy with the construction of an air pollution index, it is possible to construct a fuels emission index based on the emission standards specified under either the Australian Design Rules or the European emission standards. This task will now be undertaken on the basis of the Euro4 ETC standards for heavy vehicles.

The Euro4 standards are based on vehicle emissions in units of g/kWh, which have been converted to g/MJ. The standards are given in Table 1.6.

Table 1.6
Euro4 emissions standards (g/MJ) for heavy vehicles

Pollutant	CO	NMHC	NOx	PM	CH_4
g/MJ	1.11	0.015	0.97	0.0083	0.31

Beer et al. (2000), in Table A4.1 of their Appendix 4, provide a table of emissions for buses expressed in g/MJ. The diesel fuel in this study was regular diesel used in US buses with engines that corresponded to Euro2 standards. These are reproduced in Table 1.7. These values enable one to construct a fuels emission index based on the sum of the ratios. The ratios are determined by the ratio of the emission to the Euro4 standard. These are given in Table 1.8. The introduction of advanced technologies will lead to improvements in all of the fuels.

Table 1.7
Tailpipe emissions from urban buses (g/MJ)

Fuel	CO (g/MJ)	THC (g/MJ)	NOx (g/MJ)	PM (g/MJ)	c/km
Biodiesel	0.521	0.054	1.176	0.041	0.001
CNG	0.027	0.111	0.398	0.002	0.101
Diesel	0.092	0.055	0.736	0.023	0.001
E95	0.641	0.213	0.345	0.009	0.004
LNG	0.382	0.113	1.332	0.001	0.102

Table 1.8
Fuels emission index for each pollutant, and the summed index

Fuel	CO (g/km)	THC (g/km)	NOx (g/km)	PM (g/km)	CH_4	Sum
Biodiesel	0.5	3.6	1.2	4.9	0.0	10.2
CNG	0.0	7.4	0.4	0.2	0.3	8.4
Diesel	0.1	3.7	0.8	2.8	0.0	7.3
E95	0.6	14.2	0.4	1.1	0.0	16.2
LNG	0.3	7.5	1.4	0.1	0.3	9.7

1.5 Air Toxics

Nolan-ITU (2001) reviewed and extended the valuation of airborne pollutants based on the NSW 1998 proposed pollution controls. They recommend a value of $0.96/kg for methane (apparently equating methane with total hydrocarbons). They obtained substantially different valuations for a number of the pollutants. Particulate matter increased to a value of $9.40/kg and oxides of nitrogen increased to $3.82/kg. The most dramatic change was in the valuation for hydrocarbons. The valuation for total hydrocarbons according to the 1998 proposed pollution controls was set at $3.52/kg, but the value for chlorinated and aromatic hydrocarbons was set at $5,873/kg.

The reason for this is that the term chlorinated and aromatic hydrocarbons is being used to encompass those chemicals that cause cancer. The US EPA designated toxics emitted from conventional automobile exhaust and evaporative emissions are benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and polycyclic aromatic hydrocarbons. The US EPA also designated diesel particulate matter to be an air toxic. The Environment Australia list of priority air pollutants under the air toxics program does not include diesel exhaust, but consists of 32 pollutants, including the other ones in the US EPA list.

MacLean (1998) and MacLean & Lave (2000) calculate weighted emissions of toxics from conventional and alternative fuels. Their weighting scheme is based on the occupational health and safety based threshold limit value (in mg/m^3) for 1,3-butadiene as 4.4 mg/m^3 , a value for benzene as 1.6 mg/m^3, formaldehyde as 0.9 mg/m^3, acetaldehyde as 360 mg/m^3, and diesel particulate matter as 0.15 mg/m^3. They did not examine polycyclic aromatic hydrocarbons as such. Thus, according to these values, the diesel particulate matter is the most toxic and acetaldehyde is the least. Their results for the total emissions (in grams) over the life of a vehicle are shown in Tables 1.9 and 1.10, where Table 1.9 shows the unweighted emissions (ie the weights are unity), and Table 1.10 shows the weighted emissions.

Table 1.9
Vehicle exhaust toxic emissions (grams per lifetime) from conventional and alternative fuels (Maclean, 1998)

Fuel	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Aggregate toxics
Petrol	1540	112	252	168	-	2072
E85	161	18	672	3010	-	3861
CNG	4	0	175	20	-	199
Diesel					12,000	12,000

Table 1.10
Weighted vehicle exhaust toxic emissions (grams sulfuric acid equivalent per lifetime) from conventional and alternative fuels (Maclean, 1998)

Fuel	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Aggregate toxics
Petrol	963	25	280	0.5	-	1268
E85	101	42	747	8.4	-	860
CNG	3	0	194	0.1	-	197
Diesel					80000	80000

The calculation of toxic risk from vehicle emissions has received considerable attention in California. The procedure adopted by the Office of Environmental Health Hazard Assessment (OEHHA) is to derive the toxic risk by using unit risk factors as the weighting coefficients (Marty, 2000). Table 1.11 gives values of these toxic risk factors for emissions that are liable to occur from alternative transport fuels as reported by OEHHA (1999).

Table 1.11
Unit risk factors for carcinogenic air toxics

	Benzene	1,3-butadiene	Formaldehyde	Acetaldehyde	Diesel PM	Polyclic Aromatic Compounds
$(\mu g/m^3)^{-1}$ (Swedish study)	$8 \text{ x}10^{-6}$	$300 \text{ x}10^{-6}$	$100 \text{ x}10^{-6}$	$2 \text{ x}10^{-6}$	$70 \text{ x}10^{-6}$	$2.8 \text{ x } 10^{-2}$
$(\mu g/m^3)^{-1}$ (OEHHA, 1999)	$2.9 \text{ x } 10^{-5}$	$1.7\text{x}10^{4-}$	$6.0\text{x}10^{-6}$	$2.7\text{x}10^{-6}$	-	-
ppm (OEHHA, 1999)	$9.3\text{x}10^{-5}$	$3.7\text{x}10^{-4}$	$7.0\text{x}10^{-6}$	$4.8\text{x}10^{-6}$	-	-

An analysis from Sweden that is reported by Ospital (2000) followed a similar procedure but used substantially different unit risk factors, as also shown in Table 1.11. These values were then applied to the emissions from various alternative fuelled buses. Table 1.12 gives the comparison between the results using the Californian risk factors and the Swedish risk factors when the risk weighted emissions are normalised to that of uncontrolled ultra-low sulfur diesel, as used in Sweden.

Table 1.12
Relative Potency Weighted Emissions (Ospital, 2000)

Fuel/Treatment	Relative emissions using OEHHA risk factors	Relative emissions using risk factors from the Swedish study
Diesel	100	100
Diesel with catalyst	85	31
Diesel with particulate filter	10	37
Diesel, DPF+EGR	7.5	38
Ethanol with catalyst	4.9	88
CNG “Average”	6.1	110
CNG “BAT”	3.1	55

1.6 ADR and Fuel Quality Review Method

According to information received from Environment Australia, the Regulatory Impact Statements accompanying the 1999 Australian Design Rules for Vehicle Emissions and the Fuel Quality Standard Bill (2000) used economic weightings for the criteria pollutants determined by the NSW Environment Protection Authority. Environment Australia requested that we examine the results using these weightings as given in Table 1.13 (where it has been assumed that all NOx transforms to NO_2).

Table 1.13
ADR/FQR weights ($/tonne)

Pollutant	PM	HC	NOx	CO
$/tonne	$17,600	$1,440	$1,385	$12

These weights were examined with the results from the life-cycle analysis. The results of their application to low sulfur diesel in trucks are given in Table 1.14, and are shown for all of the fuels examined in this study in Table 1.15.

Table 1.14
ADR/FQR weights applied to exbodied emissions from low sulfur diesel

Pollutant	PM	HC	NOx	CO	
Weights	$17,600	$1,440	$1,385	$12	$/tonne
Emissions	0.428	2.62	11.0	2.71	g/km
Weighted emissions	7533	3773	15235	32.5	μ$/km

The results of Table 1.13 and Table 1.14 occasioned considerable comment when discussed with stakeholders during a forum held in June 2001. Some stakeholders (primarily representing biodiesel producers) felt that the weight assigned to PM was too high. Others (ANGVC, EPA Victoria) felt that the weighting assigned to PM was too low. We agree with the latter group. On the basis of the weightings that we were asked to use, fuels that decrease their NOx emissions are favoured over fuels that decrease particulate matter emissions. This weighting assigns greater value to the reduction of urban smog than to the preservation of human health. This is not in accord with current Australian air quality objectives as encapsulated in the desired environmental outcome of the Ambient Air Quality NEPM, namely the adequate protection of human health and well-being.

Environment Australia has requested that the following statement be included regarding the weightings:

> “Environment Australia recognises the lack of certainty in the results of the weighting exercise. These results have value in indicating the relative impact of various fuels on emissions of concern to the Commonwealth. Ultimately, however, future policy development will require the Commonwealth to determine the most cost-effective means of addressing priority pollutants/air toxics. For this reason, the Commonwealth would be concerned if stakeholders took the results of Part 3 as solely determinative of future policy directions.”

Table 1.15
Weighted emissions obtained (in µ$/km) for trucks using alternative fuels on the basis of exbodied emissions

Fuel and processing method	HC	NOx	CO	PM10	Total
LS diesel (Aus)	2173	15581	33	7716	25502
ULS diesel (Aus)	1963	13712	41	6058	21773
ULS diesel (100% hydroprocessing)	1938	13504	41	6039	21521
Fischer-Tropsch diesel	1531	15117	30	4834	21512
Biodiesel (canola)	2072	17860	20	5235	25188
Biodiesel (soybean)	2461	17694	26	5145	25327
Biodiesel (rape)	2087	18109	20	5343	25559
Biodiesel (tallow-expanded sys. boundary)	2029	17805	20	5221	25075
Biodiesel (tallow-eco.allocat.)	864	16321	864	4833	22883
Biodiesel (waste oil)	860	16294	17	4828	21998
Biodiesel (waste oil 10% original oil value)	874	16363	17	4828	22083
CNG (Electric compression)	422	2123	1	211	2758
CNG (NG compression)	461	2308	2	228	2998
LNG (from existing transmission line)	454	3210	2	103	3768
LNG (Shipped from north west shelf)	455	3235	2	108	3799
LNG (perth)	490	3797	2	451	4739
LPG (Autogas)	1595	2114	5	1703	5417
LPG (HD5)	1632	6256	5	1245	9137
LSdiesohol	2046	14310	36	6010	22402
Ethanol azeotropic (molasses-expanded sys.bound.)	1160	14072	39	5510	20781
Ethanol azeotropic (molasses-economic allocation)	1200	12227	127	5059	18613
Ethanol azeotropic (wheat starch waste)	1121	12945	39	5062	19167
Ethanol azeotropic (wheat)	2102	15831	135	5716	23784
Ethanol azeotropic (wheat) fired with wheat straw	8255	15277	299	9416	33247
Ethanol azeotropic (woodwaste)	5317	12662	168	7445	25592
Ethanol azeotropic (ethylene)	9608	16800	46	5952	32407
PULP	593	619	27	1628	2867
E10PULP (molasses-exp.sys.bound.)	482	599	23	1626	2731
E10PULP (molasses-eco.allocat.)	482	573	24	1619	2699
E10PULP (wheat starch waste)	481	574	23	1624	2703
E10PULP (wheat)	495	614	24	1626	2760
E10PULP (wheat WS)	605	605	27	1691	2928
E10PULP (wood waste)	563	567	25	1663	2819
E10PULP (ethylene)	602	628	23	1630	2883
E85PULP (molasses-exp.sys.bound.)	457	810	29	1588	2884
E85PULP (molasses-eco.allocat.)	465	474	45	1505	2489
E85PULP (wheat starch waste)	449	477	29	1576	2531
E85PULP (wheat)	628	1002	47	1588	3264
E85PULP (wheat WS)	2019	876	84	2427	5405
E85PULP (wood waste)	1489	400	60	2068	4018
E85PULP (ethylene)	2005	1176	30	1637	4848
Hydrogen (from natural gas)	516	787	2	128	1432

1.7 *Discussion*

The choice of any weighting scheme for road transport emissions must meet two criteria of acceptability. The scientific aspects of the scheme must be acceptable, and the public policy aspects of the scheme must be acceptable.

The ambient air quality NEPM declared that "the desired environmental outcome of this Measure is ambient air quality that allows for the adequate protection of human health and well-being." Ever since then it has been accepted that health-risk weighting of pollutants is the most appropriate weighting scheme. However, the science in this area is changing rapidly (Beer, 2000) so that weightings that were deemed appropriate in 1997 or 1998 may no longer be deemed appropriate today. In particular, in Table 1.4, and even more so in Table 1.15 and 1.16, the relatively high weighting (as expressed by a high price) for NOx and the relatively low weighting for particulate matter do not agree with the present consensus of the Australian health effects of the criteria pollutants as summarised in section 1.4.2. This also reflects the current view in the US. In the appendix to Ospital (2000) the California EPA states that: "It is possible to use the total PM emissions on a mass basis as a rough surrogate for the non-cancer health effects related to particulate matter emissions from both conventionally and alternatively fuelled engines".

Australian public policy in this area is also in a state of rapid flux. Environment Australia released the final draft of its Air Toxics State of Knowledge report[1] in late 2000. Both the NEPC and the EnHealth Council continue to examine the way to use risk assessment within Australia. This means that there are no agreed Australian unit risk factors to use for cancer risk. In addition, it is uncertain whether there are sufficient data on emissions from Australian conventional and alternative fuelled vehicles to enable adequate speciation of air toxics to take place.

Given the present state of knowledge in this area, the weightings adopted in the Stage 1 report, as described in section 1.4.2 of this chapter, reflect the present understanding. Cancer risks are assigned to the total hydrocarbons. The practice of using total hydrocarbons emissions as an indication of air toxics and their impacts has severe limitations. The composition of the mixture of hydrocarbons in exhaust will vary with fuel. Where total hydrocarbons is used as an indicator for relative importance of air toxic emissions the results are indicative only. Particulate matter is weighted according to recent epidemiological results. The relative magnitude of the final weighted values should be in the same proportion to the mortality attributable to each pollutant. Given that the ratio of HC to PM is in the expected ratio of 1 to 2, we conclude that in the ADR/FQR weightings (given in Table 1.14) the NOx weighting appears to be far too high in comparison to the HC and PM weightings.

However, we suspect that all the air quality valuations are too low. Representative valuations for CO_2 range from \$5 per tonne to \$500 per tonne. If we use a value of \$50 per tonne (the geometric mean of the range of estimates)[2], and note that a typical bus emits 1,300 g/km of CO_2, then the valuation associated with exbodied greenhouse gases is μ\$65,000/km for greenhouse gases emitted using low sulfur diesel, compared to about μ\$25,000/km for criteria pollutants emitted from low sulfur diesel. Surveys of the Australian public regularly reveal that air quality is considered to be a much higher environmental priority than greenhouse gases. This seems to indicate that weightings that lead to a total valuation for air quality that is about one-third that of greenhouse gases are unlikely to be correct weightings.

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[1] http://www.environment.gov.au/epg/airtoxics/sok_final_draft.html

[2] This figure has been chosen by the consultants as being a representative one for calculations. It has not been endorsed by the Australian Greenhouse Office and should not be taken to indicate a policy position on the part of the AGO.

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2. Modelling Emission Standards and Driving Conditions

2.1 Modelling the Influence of Future Emission Standards

2.1.1 Introduction

The terms of reference require an examination of the fuels to determine whether each fuel is likely to meet future Australian Design Rules for vehicular emissions. This point has been examined for each fuel in Parts 1 and 2 but is explored in more technical detail in this chapter.

An approximate method for including the effect of future emission standards was developed for the technical study on fuels technology related to the Auto Oil 2 Program. The final report by Arcoumanis (2000) was released in December 2000 by the EC's Directorate-General for Energy. This was a survey of best available information on emissions and energy efficiency for a more limited range of fuels than are considered here. It introduced the concept of emission factors related to a base of Euro2, the same base that has been followed in this work where possible. The emission factors are developed from consideration of a range of influences of alternative fuels on combustion and other engine characteristics.

2.1.2 Methods

In this project an attempt is made to estimate future emission factors by considering the changes that may occur in the near future that could influence engine and vehicle technology, and the interaction of this with the fuel. For each regulated pollutant, CO, HC, NOx, PM and for CO_2 factors have been estimated, and then these are multiplied by the ratio of the new emission standard to Euro2 for each of the regulated pollutants. For CO_2, since there are no regulated emissions standards in place at this time, the Euro3/Euro2 and Euro4/Euro2 factors were considered as unity.

No allowance has been made for the different implementation times of the Euro standards in Australia to Europe. The time lags have been regarded as technology transfer times. However, experience with emission control equipment has indicated that the lags often allow the Australian implementation of more mature technology which might be expected to improve the emission factors. Here these benefits are assumed to be the same for the low sulfur diesel reference fuel and the alternative fuel technology.

The implication in the methodology is that in the absence of any special problems or benefits the reduction in alternative fuel performance will be similar to the reduction for a given pollutant as expected from the change in the emission standards.

Engine parameters that have an effect on exhaust emissions have been divided into the following groups (Arcoumanis, 2000):

1. Engine breathing - this determines the amount of mixture/air entering the cylinders and participating in combustion which controls the mass of exhaust pollutants.
2. Mixture preparation - which influences the local fuel air ratio in the engine and has influence on pollutant formation and emissions exiting from the exhaust.
3. Combustion - this influences the formation of pollutants in the cylinder as a function of the local thermodynamic conditions.
4. Exhaust after treatment - this determines the percentage of formed pollutants escaping in the atmosphere.
5. Engine/fuel compatibility - which determines the degree of positive or negative interaction of the given of alternative fuel with components of the fuel injection system.

6. Engine deterioration in use - this depends on the maintenance standards and the state of the engines exhaust emissions and any variation with time that may vary from the standard low sulfur diesel fuel.

It is important to note that the multiplying parameter n_{total} is a product of parameters just described. Thus for a fuel where the n_{total} coefficient is 0.8, this value would express that this particular alternative fuel has some advantage compared with the low sulfur diesel reference fuel. Conversely, a coefficient of 1.5 would indicate a major difficulty with respect to the pollutants being considered. The parameter EF given the following tables thus represents the final merit of an alternative fuel including the expected reduction factor of the changed emission standards. In order to make this clear the first table presented shows the Euro factors being the ratio of Euro4 to Euro2.

In summary the following equation forms the basis for the model

$$\mathbf{EF_{Euro3/4} = EF_{Euro2} \bullet n_{total} (R_{Euro3/4} / R_{Euro2})} \tag{1}$$

where

$n_{total} = n_{br.}\, n_{mp.}\, n_{cmb.}\, n_{ea.}\, n_{fc}$

and

n_{br} = engine breathing coefficient

n_{mp} = mixture preparation coefficient

n_{cmb} = combustion coefficient

n_{ea} = exhaust after-treatment coefficient

n_{fc} = fuel/engine compatibility coefficient

$R_{Euro\ 3/4}$= regulated emission limit for a particular pollutant for Euro3/4 (in Europe in 2000/5 and Australia in 2005/8)

R_{Euro2} = regulated emission limit for a particular pollutant in 2002 (Euro2)

2.1.3 Emission factors for Euro3 and Euro4

Most of the coefficients in Equation 2.1, for the fuels given in Tables 2.1 –2.7, have values taken from the Auto-Oil II program (Arcoumanis, 2000). Where necessary, errors or inconsistencies in that work have been rectified. For some tables new factors have been generated based on the team's knowledge and this review of the literature.

The tables which follow are restricted to Factors for Heavy Duty Vehicles and Buses. Only the last table refers to PULP plus E10 for passenger cars and Light Duty Vehicles.

2.1.4 Concluding remarks

This section has evaluated, through the process used in the Auto Oil II program, the prospects and difficulties that alternative fuels may suffer as a consequence of tightening emissions standards through Euro3 and Euro4 from a base of Euro2. These results have been tabulated and presented in each Chapter of Part 2 under the heading "Expected Future Emissions".

Most fuels (including BD30) continue their relative advantages during the period of these tighter emission standards. The apparent exceptions are 100% biodiesel (PM > Euro3, NOx > Euro3 and Euro4), ethanol (THC > Euro3 and Euro4) and possibly diesohol.

Table 2.1
Future emission factors for heavy duty vehicles and buses for CNG/LNG

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.3**		**0.9**		**0.2**		**0.1**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	0.9	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	0.9	0.60	1.1	0.71	0.9	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.2	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	0.972	1.0	1.1	1.0	0.9	1.0	1
Euro 3 EF			**0.16**		**0.52**		**0.16**		**0.06**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	1.0	0.13	1.1	1
	n_{ea}	1.1	n_{total}	1.1	n_{total}	0.9	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.1	1.21	1.1	1.21	1.0	0.99	0.9	0.81	0.9	0.99
Euro 4 EF			**0.14**		**0.46**		**0.10**		**0.01**		**0.99**

Source: Arcoumanis(2000)

Table 2.2
Future emission factors for heavy duty vehicles and buses for LPG

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.4**		**0.5**		**0.3**		**0.3**		**1.1**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	0.9	0.71	1.0	0.67	0.9	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.1	1.1	1.0	0.9	1.0	1	1.0	0.9
Euro 3 EF		**0.21**		**0.33**		**0.19**		**0.20**		**0.99**	
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	0.9	1
	n_{ea}	1.0	n_{total}	0.9	n_{total}	1.1	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	0.90	1.0	1.10	0.9	0.81	1.0	0.9
Euro 4 EF		**0.15**		**0.19**		**0.17**		**0.03**		**0.99**	

Table 2.3
Future emission factors for heavy duty vehicles and buses for 100% biodiesel

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**0.8**		**0.7**		**1.0**		**1.0**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.1	0.71	0.9	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.1	1.1	1.1	1.21	1.1	0.99	1.0	1
Euro 3 EF			**0.42**		**0.46**		**0.86**		**0.66**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	0.9	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1.1	1.0	0.9	1.0	1
Euro 4 EF			**0.30**		**0.29**		**0.55**		**0.12**		**1.00**

Table 2.4
Future emission factors for heavy duty vehicles and buses for diesohol

Technology		**CO**		**THC**		**NOx**		**PM**		**Vehicle CO_2**	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.6**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF			**0.58**		**0.66**		**0.57**		**0.40**		**0.40**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF			**0.41**		**0.46**		**0.40**		**0.08**		**0.40**

Table 2.5
Future emission factors for heavy duty vehicles and buses for E85

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.6**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF		**0.58**		**0.66**		**0.57**		**0.40**		**0.40**	
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF		**0.41**		**0.46**		**0.40**		**0.08**		**0.40**	

Table 2.6
Future emission factors for heavy duty vehicles and buses for hydrogen (Combustion Engine)*

Technology		**CO**		**THC**		**NOx**		**PM**		**Vehicle CO_2**	
Euro 2 EF		**0.05**		**0.02**		**0.2**		**0.01**		**0.01**	
Euro 3	n_{br}	0.9		0.9		0.9		0.9		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	0.9	0.53	0.9	0.60	1.1	0.71	0.2	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	0.765	1.0	0.765	1.0	0.935	1.0	0.17	1.0	1
Euro 3 EF			**0.02**		**0.01**		**0.13**		**0.00**		**0.01**
Euro 4	n_{br}	0.9		0.9		0.9		0.9		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.1	0.50	0.2	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	0.85	1.0	0.85	1.0	0.935	1.0	0.17	1.0	1
Euro 4 EF			**0.02**		**0.01**		**0.09**		**0.00**		**0.01**

* Fuel Cell vehicles assumed to emit only water vapour.

Table 2.7
Future emission factors for passenger cars and light duty vehicles for PULP

Technology		**CO**		**THC**		**NOx**		**PM**		**Vehicle CO_2**	
Euro 2 EF		**0.4**		**0.4**		**0.4**		**0.4**		**0.4**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 3 EF			**0.21**		**0.24**		**0.29**		**0.27**		**0.40**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1	1.0	1	1.0	1	1.0	1	1.0	1
Euro 4 EF			**0.15**		**0.17**		**0.20**		**0.05**		**0.40**

Table 2.8
Future emission factors for passenger cars and light duty vehicles for E10PULP

Technology		CO		THC		NOx		PM		Vehicle CO_2	
Euro 2 EF		**1.1**		**1.1**		**0.8**		**0.5**		**1.0**	
Euro 3	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.1	R_3/R_2	1.1	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2	1.0	R_3/R_2
	n_{cmb}	1.0	0.53	1.0	0.60	1.0	0.71	1.0	0.67	1.0	1
	n_{ea}	1.0	n_{total}	1.1	n_{total}	1.1	n_{total}	1.0	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1.1	1.0	1.21	1.0	1.1	1.0	1	1.0	1
Euro 3 EF			**0.64**		**0.80**		**0.63**		**0.33**		**1.00**
Euro 4	n_{br}	1.0		1.0		1.0		1.0		1.0	
	n_{mp}	1.1	R_4/R_2	1.1	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2	1.0	R_4/R_2
	n_{cmb}	1.0	0.38	1.0	0.42	1.0	0.50	1.0	0.13	1.0	1
	n_{ea}	1.0	n_{total}	1.1	n_{total}	1.1	n_{total}	0.9	n_{total}	1.0	n_{total}
	n_{fc}	1.0	1.1	1.0	1.21	1.0	1.1	1.0	0.9	1.0	1
Euro 4 EF			**0.45**		**0.56**		**0.44**		**0.06**		**1.00**

2.2 Modelling the Influence of Driving Conditions.

2.2.1 Introduction

The terms of reference require an examination of the fuels to determine approaches that would enable the downstream emissions from fuel and technology combinations to be approximated without conducting a large scale tailpipe emissions testing program.

This section of the chapter provides an initial appreciation of the effect of a range of urban and rural driving conditions on the greenhouse gas emissions of selected fuels. All of the results in the comparison of emissions with the base line diesel fuel have been made using data from the Euro 2 test schedule for vehicles or engines. The weighting applied to the 13 modes of this engine test schedule is somewhat arbitrary, reflecting a simplistic allocation of engine load and speed. The reference vehicles are a conventional diesel engined, standard 59 seat bus and a 45 tonne articulated truck..

2.2.2 Modelling methodology

The model used for the analysis is a deterministic one, of the engine mapping type. The computer program, MEEDAM (Model for Emissions and Energy Dissipation for Analysis of Missions) is a derivative of the main-frame models first used in late 1980's (Khatib and Watson, 1986) and developed for the SAE-A, as a commercial package, to allow operators when purchasing new trucks to be informed on the relative fuel efficiency of variants available from the manufacturer.

Central to the model are measured maps of engine performance, which describe an engine's emission or fuel rate use over the usable range of torque (positive and negative) and engine speed. The engine maps comprise emission rates of hydrocarbons, oxides of nitrogen, carbon monoxide or particulates and fuel rate for energy consumption simulation. Here, only steady state maps are employed, although when available maps in speed and torque time-derivative domains may be included. In comparative (sensitivity) analyses this limitation is not as important as in the calculation of absolute values of fuel consumption and CO_2 emissions. In any event, at the end of a period of ten or more minutes driving, the net contribution of the transient fuel supply is quite small, perhaps 3% of the total (Trayford and Watson, 1999).

An outline of the model is presented in Figure 2.1. At a given vehicle speed and acceleration the first step is the calculation of the instantaneous wheel torque and the selected gear ratio. The wheel torque is calculated from the rolling resistance, aerodynamic drag, inertial forces (linear and rotating). The transmission losses and engine auxiliaries' torque are added to the wheel derived torque to define the instantaneous engine speed and torque and thus the fuel rate is calculated from the map

Gear selection to simulate a manual transmission is made by an algorithm that uses shift points as a function of vehicle speed and acceleration.

For an automatic transmission the gear ratio selected is a function of engine speed and torque ratio to allow for torque converter slip, the coefficients for which came from an analysis of bus four speed automatic performance.

The final drive efficiency is a function of rotational speed and torque transmitted. More details of example applications are to be found in references Watson and Alimoradian (1989) and Watson (1995).

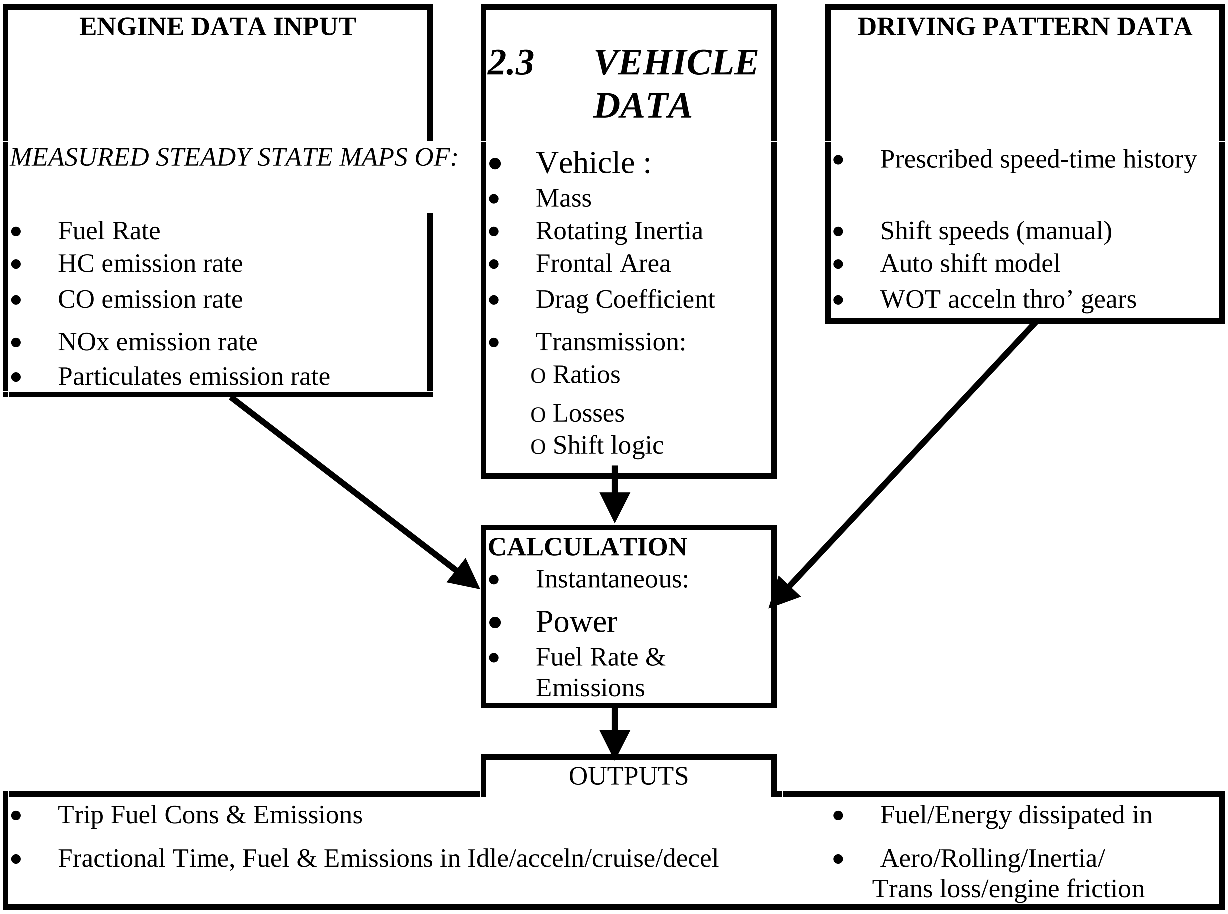


Figure 2.1
Model inputs and outputs

The model includes allowance for road gradient and wind speed and direction. Both of these effects have considerably more effect on trucks and buses than is found in passenger cars, because of their relatively poor power in proportion to size and weight.

Two examples follow to illustrate the effect of the change in liquid fuel composition and the change of fuelling system (liquid to gas).

2.2.3 Results of changed fuel - diesohol example

The test results in this section refer to earlier diesohol trials and are used for illustrative purposes only. Current emissions data for diesohol is provided in Parts 1 and 2.

The data for this comparison were obtained from the NSW EPA for the diesohol bus trial, which was conducted in 1993/4. The buses used in the test and simulated in the model were Renault/Mack buses operated by Action Buses in Canberra. The thirteen mode Euro 2 test was modified slightly by the EPA to produce the database, which nonetheless allowed the development of the relevant engine maps for modelling.

Figure 2.2 shows the CO_2 emissions rate for the bus No. 977 operated on diesohol fuel compared with diesel for a range of established test cycles. The average speed of these cycles forms the base of the graph. The cycles include the fuel consumption cycle AS2877 City and AS2877 Highway normally used for car and light commercial vehicles testing. However, experience has shown that buses can also perform satisfactory on these cycles. Also included are an urban truck and a highway truck cycle based on measurements made in Sydney and Melbourne and the interstate highways between Brisbane, Sydney and Melbourne in the period 1986/7. (Khatib 1987).

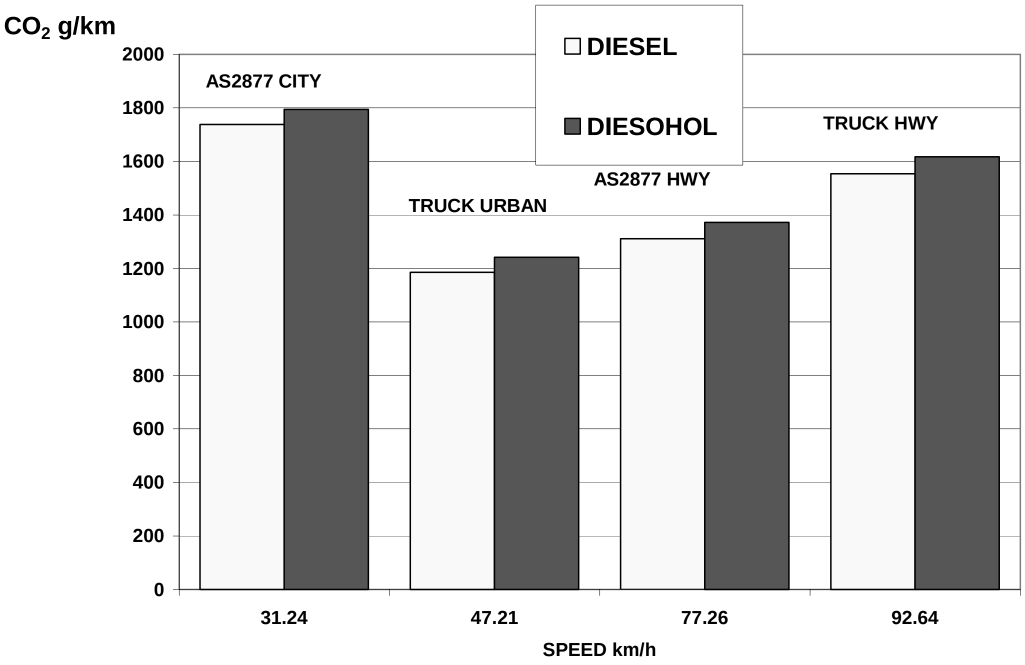


Figure 2.2
Variation in CO_2 emissions for the simulated bus over AS2877 and truck cycles for diesohol and reference diesel fuel

In Figure 2.3 a similar set of values are presented on the basis of driving as measured recently as part of the Diesel NEPM developed two years ago NEPC (1997). These cycles are disaggregated into congested, residential, arterial and highway driving. All were based on driving in Sydney.

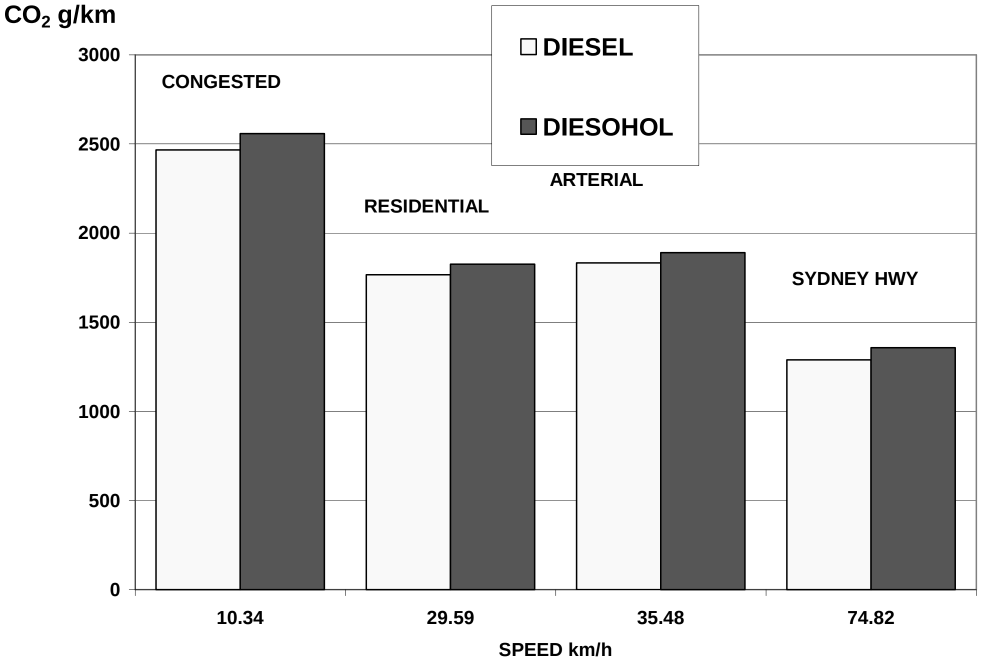


Figure 2.3
Variation in CO_2 emissions for the simulated bus over CUEDC developed as part of the diesel NEPM

It can be seen in each of the figures under all conditions that the diesohol bus has slightly higher CO_2 emissions than the diesel reference bus.

These sample results are now expressed as a ratio in Figure 2.4 - the ratio of the CO_2 emissions in the diesohol mode is compared with the CO_2 emissions in the diesel mode. It can be observed that the ratio varies between 1.031 to 1.053 with an average value of 1.038. The average value for the weighted Euro 2 cycle was 1.034.

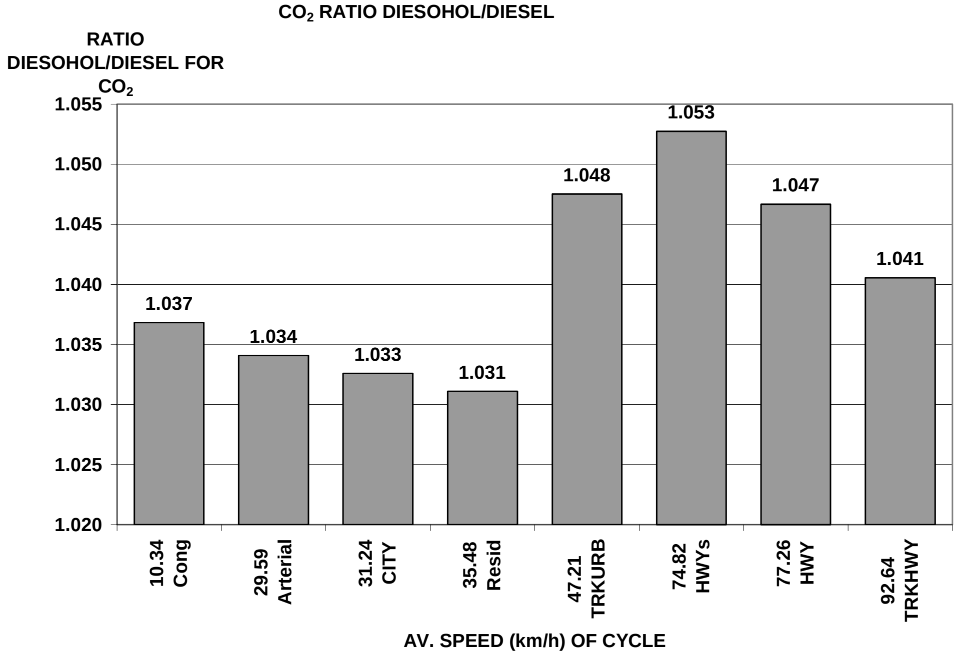


Figure 2.4
Ratios in CO_2 emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

It may be thought that the variation in CO_2 emissions with driving is very small. However, it should be recalled that diesohol comprises only 15% which replaces only about 9% of diesel fuel energy. Thus, with a 9% replacement in energy a 2% variation in CO_2 emissions is nearly 25% variation in the replaced $CO_{2.}$

Similar ratios are plotted for NOx and smoke emissions in figures 2.5 and 2.6 respectively. There is a general trend for these to be lower in the urban conditions and higher in highway driving. Overall there is a slight increase in NOx and a small reduction in exhaust smoke and therefore particulates.

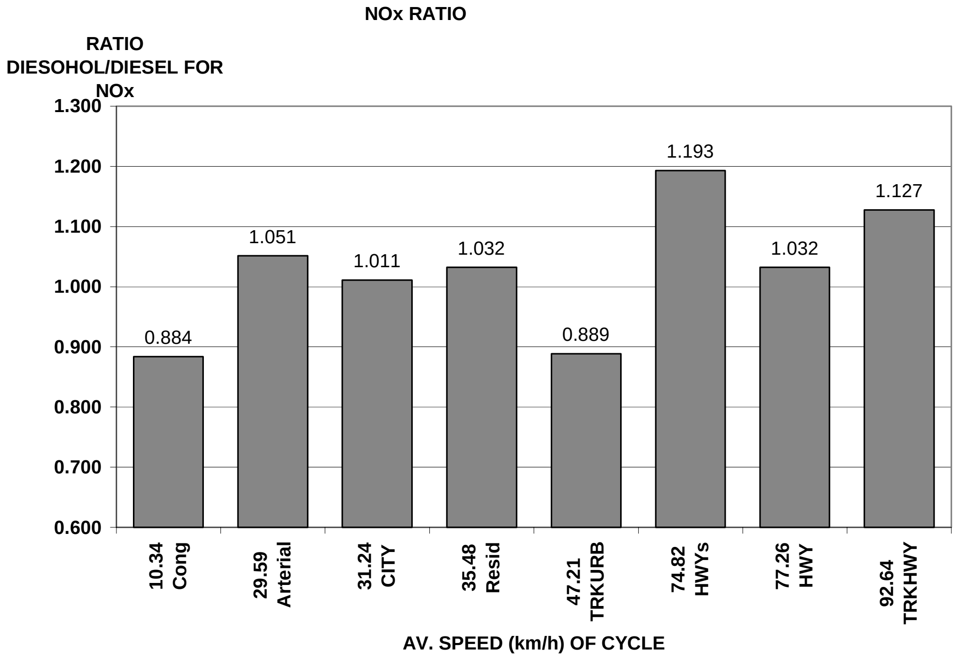


Figure 2.5
Ratios in NOx emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

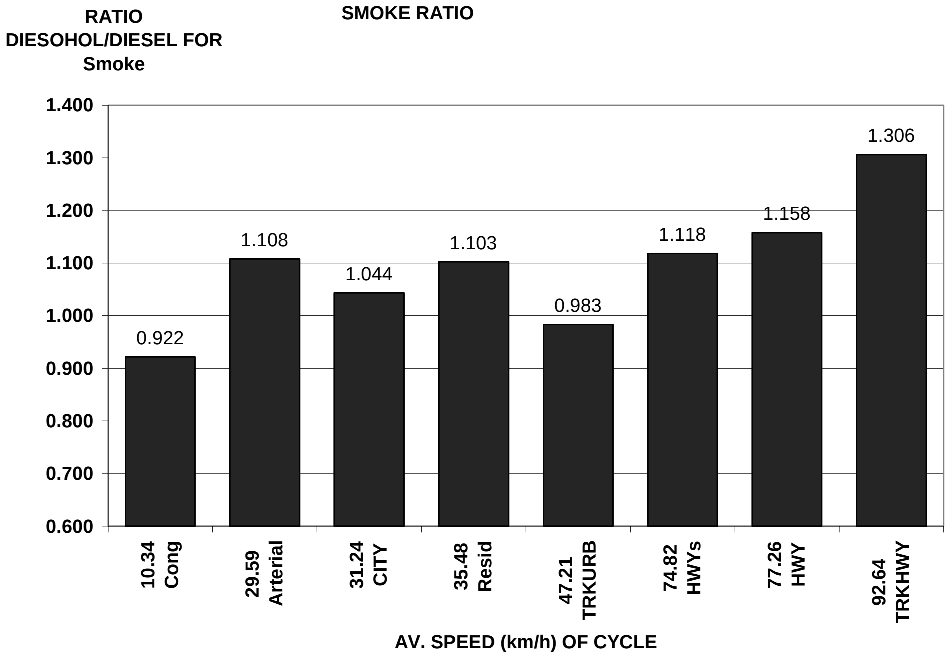


Figure 2.6
Ratios in Smoke emissions for diesohol compared with diesel fuel the simulated bus over the eight cycles

2.2.4 Results for changed fuel supply system, example - dual fuel CNG

This simulation is for an articulated truck with a minimum GVM of 15 tonnes and a maximum of 45 tonnes. It is powered by a 450HP engine sourced from the US and drives through a 12 speed transmission and dual axle drive.

As no Euro 13 mode data was available in the open literature for a spark ignited CNG vs diesel comparison, the simulation was performed for a dual fuel engine with 65% CNG substitution of gas for diesel over the 13 mode test schedule with the standard's weighting factors.

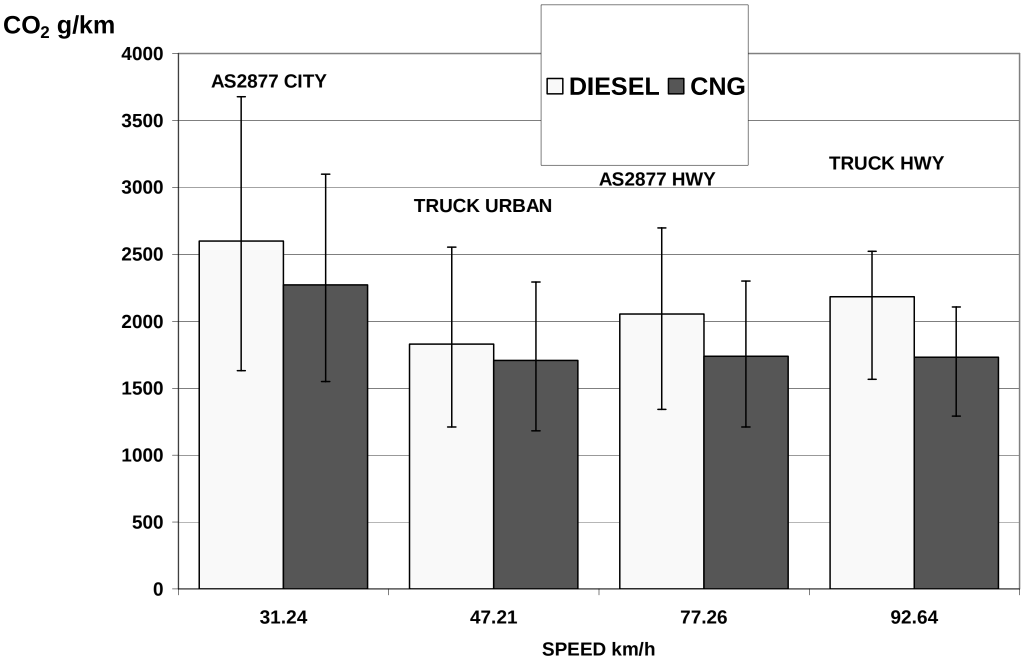


Figure 2.7
Variation in CO_2 emissions for the simulated truck over AS2877 and truck cycles for dual fuel CNG and reference diesel fuel

The bars are for 30 tonnes half-laden condition. The error bars show the 45 tonne and 15 tonne conditions.

The results in Figure 2.7 show CO_2 emissions for the simulated truck over AS2877 and truck cycles for the dual fuel CNG and LSD diesel fuel. The major bars are for 30 tonnes half laden condition, whilst the error bars show the 45 tonne fully laden and 15 tonne unladen conditions. It is noticeable that there is a significant variation of emission with load condition and relatively small variation with speed except for the aggressive-for-a-truck car city cycle. Indeed in the unladen condition the reduction in CO_2 is 7% compared with 18% under full load. This trend is expected as the CNG substitution tends to increase in proportion to the power output.

Similar conclusions may be drawn for the CUEDC cycles in Figure 2.8

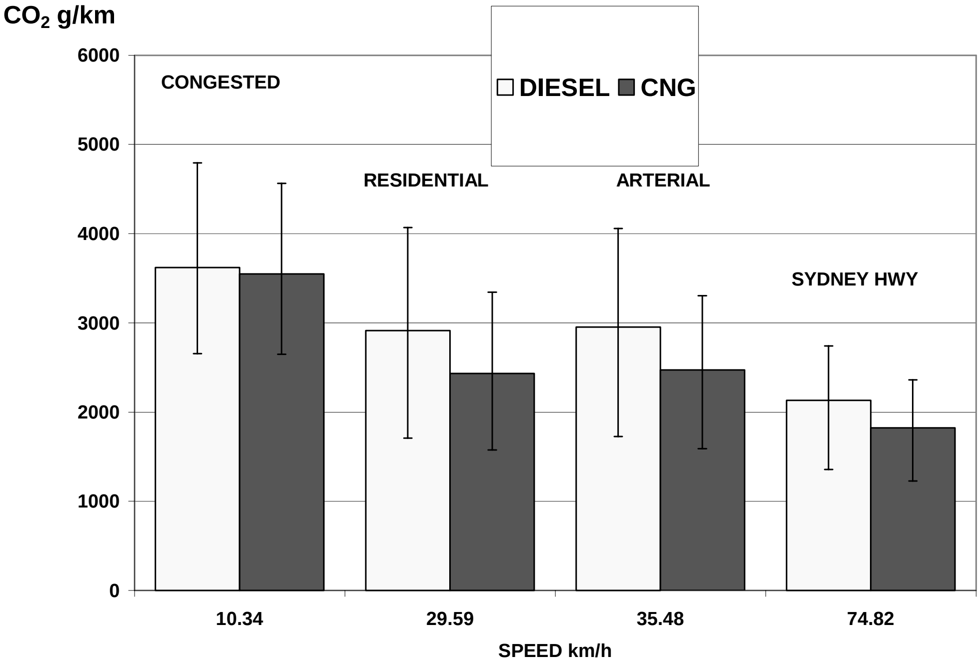


Figure 2.8
Variation in CO2 emissions for the simulated truck over CUEDC developed as part of the diesel NEPM. for dual fuel CNG and reference diesel fuel

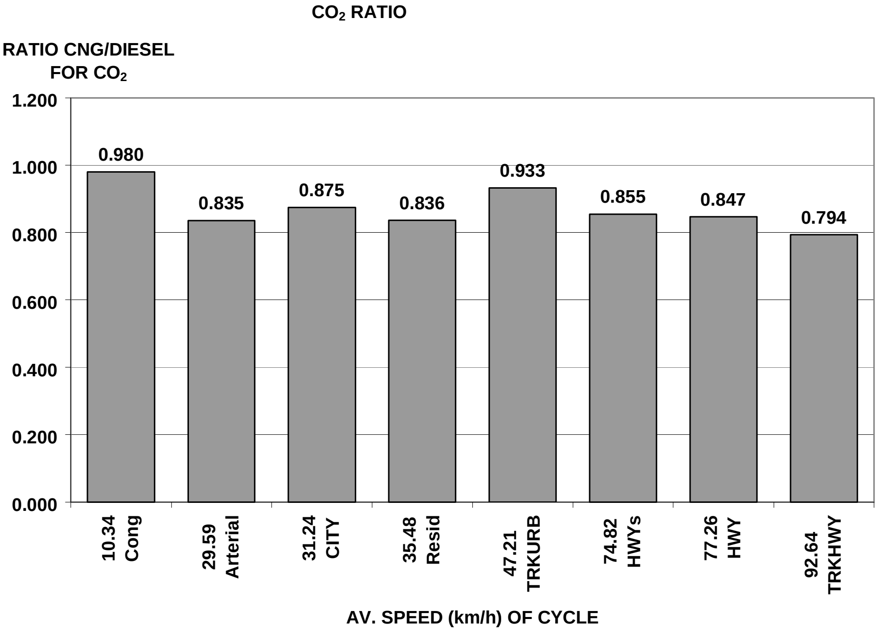
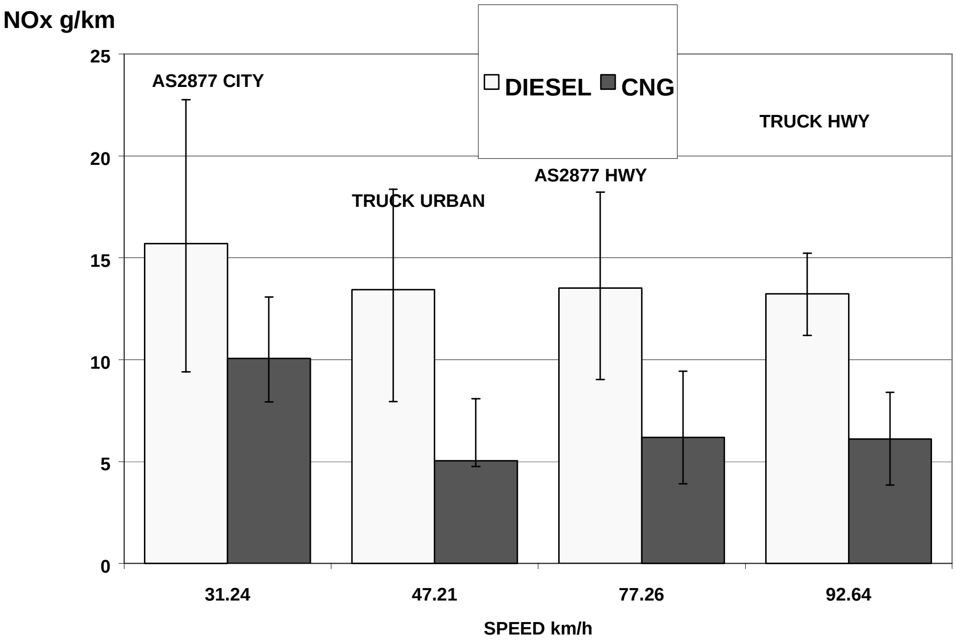


Figure 2.9
Ratios in CO_2 emissions for dual fuel CNG compared with diesel fuel for the simulated truck over the eight cycles

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

Figure 2.9 shows ratios in CO_2 emissions for dual fuel CNG/diesel fuel for the simulated truck over the eight cycles for a vehicle mass of 30 tonnes. The reduction in combustion CO_2 is about 16% on average.

Figure 2.10



Variation in NOx emissions for the simulated truck over AS2877 and truck cycles for dual fuel CNG and reference diesel fuel

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

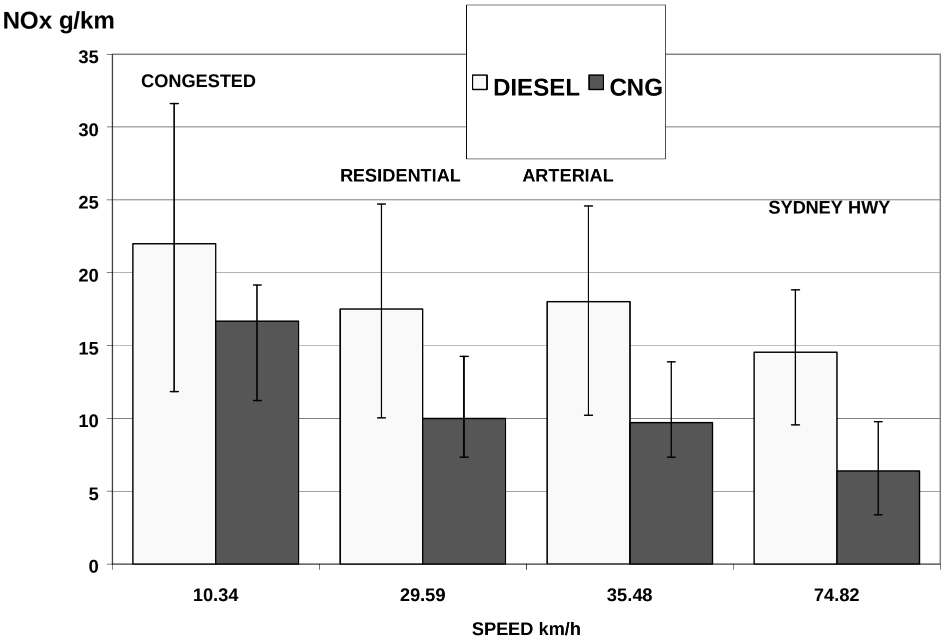


Figure 2.11
Variation in CO_2 emissions for the simulated truck over CUEDC developed as part of the diesel NEPM. for dual fuel CNG and reference diesel fuel.

The bars are for 30 tonnes half laden condition. The error bars show the 45 tonne and 15 tonne conditions.

The NOx emissions in Figures 2.10 and 2.11 demonstrate more pronounced reductions in NOx emissions with increased vehicle mass with reductions in excess of 40% under the fully laden condition. The ratios of CNG dual fuel to diesel at the 30 tonne mass condition are shown in Figure 2.12 where the trend for reducing NOx with increasing speed is evident. This of course means that the NOx emission benefit is not so great where it matters most in urban areas.

Unfortunately the data on CNG dual fuel did not cover particulate emissions.

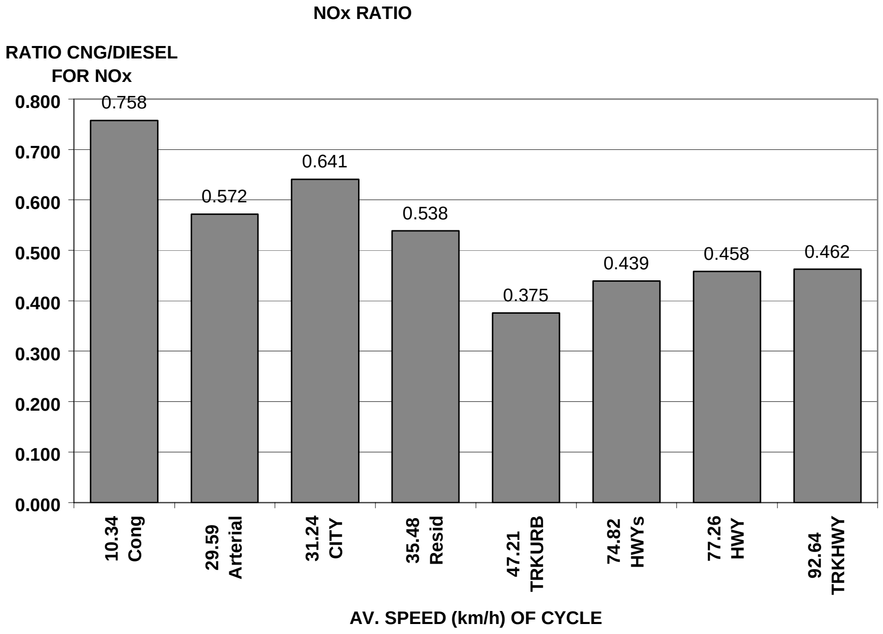


Figure 2.12
Ratios in NOx emissions for dual fuel CNG compared with diesel fuel for the simulated truck over the eight cycles

2.2.5 Conclusions

In this section we have examined two examples of alternative fuels application to heavy-duty vehicles, a bus and a truck. In the first example the impact of a change fuel composition (to dieshol) which showed that the CO_2 emissions might increase somewhat more in real world driving from the expected increase in the Euro 2 steady state test. However the increase is small, and other tests have shown an opposite trend,

In contrast the example of a changed fuel application of CNG to a large truck the real world CO_2 emissions were somewhat better than expected from the Euro 2 base.

Whilst this has only been a limited illustration of the available methodology for modelling these changes, the method does provide a workable basis for the estimation of emissions from alternative fuel vehicles in a range of driving circumstances which include interstate highway and urban situations including congested and free driving conditions. This information should be useful for those involved in undertaking analysis of transport emission sources or CO_2 emissions inventories.

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Appendix 1. Terms of Reference for Comparison of Transport Fuels – Stage 2

A1.1 Background

The Australian Greenhouse Office (AGO) supported the development of the Diesel and Alternative Fuels Grants Scheme (DAFGS) which maintains price relativities between diesel and alternative fuels following the reduction in the diesel fuel excise rate and the provision of grants for diesel used for on-road transport from July 2000.

The Scheme is administered by the Australian Taxation Office (ATO) but the Chief Executive of the AGO is responsible for certifying additional alternative fuels as being eligible under DAFGS. This analysis will assist in determining the eligibility of several fuels currently not eligible under the Scheme. The study will also provide a profile of emissions for a broad range of conventional and alternative fuels under Australian conditions that will inform future policy for transport fuels.

Further information about DAFGS can be found using the search facility on the ATO website www.ato.gov.au and information about the AGO transport programs are available from www.greenhouse.gov.au/transport

The Stage 1 study (referred to in section 4) was based on the assessment of existing studies of transport emissions. Stage 2 builds on this work and requires extensive liaison with industry, government and other key stakeholders when developing the emissions profile.

A1.2 Definition

For the purpose of this study, “full fuel cycle emissions” are emissions of a fuel product generally from when a raw material is extracted (for fossil fuels) or planted (for renewable fuels) to when the fuel is combusted. The study of full fuel cycle emissions would include the following processes:

- extraction
- production;
- transportation and storage;
- fuel processing;
- conversion;
- fuel transportation, storage and distribution; and
- vehicle operations that involve fuel combustion or other chemical conversions.

The processes that precede vehicle operations are generally referred to as upstream activities; and vehicle operations are referred to as downstream activities.

A1.3 Objectives

The objective of Stage 2 is to examine the emissions and other characteristics of transport fuels that will assist the Chief Executive of the AGO to determine which additional alternative fuels should be considered for eligibility under the DAFGS, and to provide a profile of each transport fuels' emissions (both current and projected to 2006).

The objective will be achieved through:

1. a comparison of road transport fuel emissions through a full fuel cycle analysis of greenhouse gas emissions and emissions affecting air quality; and,

2. for each fuel, an assessment of current and near future (ie to 2006):

- viability and functionality;
- health related issues; and
- environmental issues (including ecologically sustainable development) not related to greenhouse or air quality issues.

A1.4 Scope

Stage 1 Analysis

The analysis of alternative fuels is being conducted in two stages. Stage 1 was limited to an overview of Australian and overseas studies that assess the emissions characteristics of alternative and conventional fuels that are or may be suitable for use in road vehicles from 4.5 tonnes gross vehicle mass (GVM).

The fuels assessed in Stage 1 were compressed natural gas (CNG), liquefied petroleum gas (LPG), liquefied natural gas (LNG), recycled waste oil, canola oil, ethanol, as well as a range of blends of these fuels, including biodiesel and conventional fuels such as low and ultra low sulfur diesel.

The greenhouse gases assessed in the Stage 1 analysis included carbon dioxide, nitrous oxide, and methane. Air pollutants assessed were carbon monoxide, oxides of nitrogen (the NOx group), oxides of sulfur (SOx), non-methane volatile organic compounds (NMVOCs), visible smoke and particulates. The analysis also examined greenhouse gas emissions and air pollutants in the upstream activities of a fuel's life cycle. Stage 1 has been completed and a copy of the report is on the AGO website at: www.greenhouse.gov.au/transport/pdfs/lifecycle.pdf

Requirements for Stage 2

Stage 2 will:

- conduct a full fuel cycle analysis of emissions for onroad transport fuels;
- determine whether any fuel has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period to 2006 (inclusive);
- examine the viability and functionality of the fuels;
- examine significant health related issues from the use of the fuels; and
- examine other significant environmental issues resulting from the use of the fuels including ecologically sustainable development.

Stage 2 will include the following.

Full Fuel Cycle Analysis

1. Collect data on emissions for the specified fuels from production to combustion in onroad vehicles taking into account Australian conditions for fuel production.

2. Objectively assess the emission characteristics of the specified fuels.

3. Determine whether any fuel has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period up to and including 2006.

Low sulfur diesel (ie 500ppm or less) will be used as an emissions benchmark against which other fuels are compared. Section 5 *Full Fuel Lifecycle Analysis* describes in detail the requirements for the analysis.

Viability and functionality

4. Taking into account existing and emerging technologies* examine:

- handling, transport, storage and safety issues focussing on significant risks associated with the use of the fuel;
- engine manufacturers' acceptance of the fuel for warranty purposes;
- the functionality of the fuel under the full range of Australian conditions (eg consider: the significance of problems associated with the cloud point temperature or the fuel's affinity for water; the effect of fuels on engine seals; and engine and other components' longevity);
- fuel energy density and vehicle operational range;
- refuelling requirements;
- issues affecting the availability of fuel and;
- other issues (except for price/excise/grant/cost related issues) that may affect the viability or functionality of the fuel.

* Refer to *Review of Fuel Quality Requirements for Australian Transport* Chapter 2 (commissioned by Environment Australia) for a definition of existing and emerging technologies applying to diesel engines. A copy can be found at: http://environment.gov.au/epg/fuel/transport.html

Health Issues

5. Examine key health issues resulting from the production, transport and use of the fuel. Among other issues, special attention should be paid to: occupational health and safety issues; particulates; vapour pressure (the main concern being evaporative emissions) and the following air toxins:

   - benzene;
   - 1,3 butadiene;
   - formaldehyde;
   - acetaldehyde;
   - polycyclic aromatic hydrocarbons (PAH);
   - toluene; and
   - xylene

Environmental Impact and Benefits

6. Examine significant environmental impacts not included under the fuel cycle analysis resulting from the production, transportation or use of each fuel. This section of the study will include, but not be limited to an examination of:

   - the use of technologies or additives associated with the fuel;
   - whether any of the principles of ecologically sustainable development are at risk of being compromised through the production, distribution and use of the fuel (refer to section 3A of the Environment Protection and Biodiversity Conservation Act 1999 for the definition of ecologically sustainable development - copy attached)
   - the sustainability of fuel production and use (eg impact on land used for biofuels); and
   - spillage issues including groundwater contamination.

A1.5 Fuel Types

The fuels to be examined and their specifications are:

- Low sulfur diesel (LSD) meeting either Euro II fuel specifications or the fuel specifications for LSD proposed by the Commonwealth for implementation in 2002. Refer to http://www.environment.gov.au/epg/fuel/pdfs/fuel0900.pdf *
- Ultra-low sulfur diesel (ULSD) meeting either Euro IV specifications or the fuel specifications for ULSD proposed by the Commonwealth for implementation in 2006. Refer to http://www.environment.gov.au/epg/fuel/pdfs/fuel0900.pdf
- Compressed natural gas (CNG) as defined in Australian standards.
- Liquefied petroleum gas (LPG) autogas grade from any source meeting the voluntary ALPGA specification or European standard EN589.
- LPG - HD5 grade from any source. Refer to Californian Air Resources Board specifications http://www.arb.ca.gov/regact/lpgspecs/lpgspecs.htm
- Ethanol - hydrated - from renewable sources (wheat, sugar cane, molasses and wood) and one source of ethanol from a non-renewable resource.
- Ethanol - anhydrous - from renewable sources (wheat, sugar cane, molasses and wood) and one source of ethanol from a non-renewable resource.
- Diesohol from APACE Research. The fuel is known as E15 and consists of 84.5% diesel, 15% hydrated ethanol (ethyl alcohol containing approximately 5% water) and 0.5% emulsifier.*
- Liquefied natural gas (LNG) as defined by European or US standards.
- Canola oil (ie not biodiesel).
- Biodiesel. Examine biodiesel meeting either of two major fuel specifications - European DIN V 51606 standard or the US standard ASTM PS121. Consider biodiesel produced from a range of feedstocks including tallow, recycled waste cooking oil, canola, rapeseed and soybean.*
- Synthetic diesel derived from natural gas using the Fischer Tropsch method.
- Hydrogen derived from a range of production methods and feedstock sources likely to be used in Australia. It is acknowledged that hydrogen is an energy carrier rather than a fuel but for the purposes of this study it will be described as a fuel. The study would only examine the upstream emissions.
- Premium Unleaded petrol (PULP) (95 RON) meeting either the Euro II specification for unleaded petrol or the fuel specifications for PULP proposed by the Commonwealth for implementation in 2002. Assume that this fuel does not contain ethanol and that it is used in light vehicles as defined in ADR 79/00 and 79/01. Refer to http://www.environment.gov.au/epg/fuel/pdfs/fuel0900.pdf
- PULP (95 RON) as specified above but with 10% ethanol. Assume that it is used in light vehicles.
- A-55. The fuel consists of 30-55% water, 45% naphtha, and small amounts of a blending agent. Developed in the USA in 1994 by Rudolph Gunnerman *of Clean Fuels Technology Inc* and is being promoted in Australia by *A-55 Australia*. **(Note: this fuel may be deleted from the list at any time up to 30 April 2001 and so should be considered last.)**

* Asterisked fuels will be examined first to enable a decision to be made about their possible inclusion under the Diesel and Alternative Fuels Grants Scheme. LSD will also be examined in the first group as it will be the emissions benchmark.

Where testing is undertaken by the consultant, the following information must be provided:

- for biodiesel, a certificate of analysis for the batch that identifies its density and cetane number or index, sulfur content and distillation point (degrees Celsius T90 and T95);
- for diesel or diesohol, a certificate of analysis for the batch that identifies its density and cetane number or index, sulfur content, polyaromatics and distillation point (degrees Celsius T90 and T95); and
- for gaseous fuels, a certificate indicating that they meet specifications as outlined above.

The successful tenderer will be responsible for managing and meeting all costs associated with sourcing the fuels required for any testing deemed to be necessary. A large-scale emission-testing program is not expected to be undertaken as a part of this project.

A1.6 Full Fuel Cycle Analysis

Upstream

The consultant is required to collect Australian data associated with all upstream activities of fuel cycle emissions for the fuels listed above. The derivation of the data should be clearly explained in a highly detailed manner utilising fuel cycle process trees and all assumptions must be fully explained. The data and data sources should be documented in a report that incorporates a comprehensive analysis of uncertainties regarding the data and how these uncertainties were resolved in order to determine values for the variables. All data collected will be made available in appendices and in electronic format.

To ensure the relevance of the upstream study to Australian conditions, it is crucial that extensive consultation be conducted with key Australian industry stakeholders involved in upstream activities associated with the fuel.

Where fuels have a range of production methodologies, the more common approaches used for fuels produced in, or imported into, Australia should be modelled. For example, biodiesel can be produced from an oilseed, recycled waste cooking oil and tallow. The greenhouse and air quality emissions from these approaches should be examined. A similar approach should be adopted for ethanol (which can be produced from sugar cane, molasses, wood, wheat and coal), LPG, hydrogen, LNG and other fuels which have more than one main upstream source.

For each fuel type with more than one upstream source, an indication of the likely Australian market share from each source within that fuel type will be indicated. The emissions from each upstream source will be modelled and combined with downstream emissions.

Downstream - Current and Future

A range of reputable and recent Australian and overseas studies will be considered in order to determine the relative downstream emissions of each fuel. Where possible, reports from sources using identical or similar testing methods should be used to enable the emissions to be compared. Allowances should be made for improvements in technology if reference is made to studies more than three years old.

It is important the Consultant collect certified emissions data produced by independent testing/measurement organisations using certified equipment/facilities following internationally recognised test methods/cycles. Collection of such data will have priority over collection of emissions data produced and/or funded by fuel producers, fuel users and industry associations.

Following consultation with key industry stakeholders, the consultant will comment about likely improvements in emissions from vehicles using each fuel in the near future as a result of improved fuels or technologies. This information will be included in a separate series of downstream emissions calculations. The consultant will also use this information as the basis for determining whether any fuel has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period up to and including 2006 for both light and heavy duty vehicles.

Emissions

The nominated emissions to be considered in the analysis are:

- key transport greenhouse gases ie carbon dioxide, nitrous oxide, methane;
- oxides of nitrogen;
- oxides of sulfur (including a calculation of oxides of sulfur emitted following combustion);
- particulate matter less than 10 microns (also considering matter less than 2.5 microns and less than 1 micron if available);
- carbon monoxide;
- total hydrocarbons;

Emission measurements will be provided in:
- grams of emission type per megajoule.
- grams per tonne-kilometre for freight vehicles; and
- grams per passenger-kilometres for passenger transport.

All emissions affecting air quality will be weighted and combined into a single measure of air quality. The quantity of upstream emissions affecting air quality not produced in metropolitan areas will be included and will also be separately noted. This task involves the development of a weighting scheme for air quality. The consultant is required to develop and submit the weighting methodology to the Steering Committee for approval as soon as possible after the commencement of the project. No preliminary reports indicating weighted air quality results are to be discussed outside of the project team prior to the approval of the weighting methodology.

Greenhouse gas emissions will be weighted using IPCC 100 year global warming potentials.

New Models for Calculating Downstream Emissions

The AGO wishes to explore alternative approaches for approximating downstream emissions involving fuel and technology combinations (eg comparing the emissions from a CNG Euro II standard engine with a diesel Euro III standard engine). It is not considered that a large scale tailpipe emissions testing program is warranted. In addition, it is extremely difficult to arrange statistically valid samples for a broad range of fuel and technology combinations. Consequently such an approach is not being considered.

The consultant is required to identify and describe approaches that would enable the downstream emissions from fuel and technology combinations to be approximated without conducting a large scale tailpipe emissions testing program.

Information Required for a Downstream Model Using ADR Specified Emissions

The consultant is also required to undertake additional research outlined later in this section associated with a method for calculating emissions under which downstream emissions affecting air quality are deemed to be equal to the maximum emissions allowable under the ADRs to which vehicles have been certified.

It may be possible to calculate downstream greenhouse gas emissions from some ADR emission standards because they refer to key greenhouse gas emissions. For example:

- methane is referred to in ADRs 80/00 and 80/01 for gas fuelled heavy vehicles under the Euro III and IV European Transient Cycle (ETC) test emission limits;
- nitrous oxide is present in NO_x referred to under ADR emissions standards;

- the light duty vehicle emission test in ADR 37/01 provides the basis for calculating CO2 emissions provided that the carbon content of the fuel is known. (Carbon dioxide emissions for heavy vehicles should also be calculated.)

To assist with the exploration of this approach, the consultant is required to:

1. determine whether each fuel is likely to yield Euro standard "X" emissions when used in a Euro "X" designated engine for both light and heavy vehicle ADR emissions standards (without additional after treatment adopted for the specific fuel in question);
2. comment on the feasibility of reasonably approximating N_2O emissions from NO_x levels referred to in the Euro standards for both heavy and light vehicles across the specified fuel types. (If feasible, the calculations will be made and the margin of error indicated.);
3. determine the value of the CO_2 emission factor for each fuel (in grams per megajoule) which would be used to determine CO_2 emissions from the fuel (ie not the CO_2 *equivalent* emissions). (In order of preference the sources are to be used are: existing Australian Greenhouse Office data, IPCC data or primary data obtained from laboratory analysis of the carbon content of the fuel.); and
4. determine an average "grams of emission per megajoule" equivalent for both greenhouse emissions and air quality emissions for both light and heavy vehicle Euro Standards I to IV. (The light vehicle Euro Standards are measured in grams per kilometre and each of the light vehicle Euro standards has three vehicle categories.)

A1.7 References

The following references, among others, should be considered:

- *A Full Fuel Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas* (US Department of Energy report dated December 1999) www.transportation.anl.gov/ttrdc/publications/pdfs/esd-40.pdf
- *Effects of Fuel Ethanol Use on Fuel Cycle and Energy and Greenhouse Gas Emissions* (US Department of Energy report, January 1999) - an electronic version is available from the AGO
- *Health and Environmental Assessment of the use of Ethanol as a Fuel Oxygenate* (US Department of Energy report, December 1999) http://www-erd.llnl.gov/ethanol
- *Air Quality Impacts of the Use of Ethanol in California Reformulated Gasoline* (California Environment Protection Agency, December 1999) http://www.arb.ca.gov/cbg/ethanol/ethfate/airq/mainf.pdf
- US EPA and National Biodiesel Board reports on biodiesel. Tier I (emissions) report completed March 1998 and Tier II (health) report produced mid 2000 (approximately May - June).
- reports from the *Diesel National Environment Protection Measure* which can be obtained through Environment Australia website http://www.environment.gov.au/
- *Alternatives to Traditional Transportation Fuels 1994 Greenhouse Gas Emissions* by the US Dept of Energy www.eia.doe.gov/cneaf/pubs_html/attf94_v2/exec.html#head4
- test results on diesohol will be available from APACE Research
- US EPA Tier I and Tier II and US DOE test results for other fuels should also be considered.

ATTACHMENT

Ecologically Sustainable Development

As indicated in these Terms of Reference, the consultant will be required to broadly consider the principles of ecologically sustainable development which are outlined section 3A of the Environment Protection and Biodiversity Conservation Act 1999.

Section 3A of the Environment Protection and Biodiversity Conservation Act 1999

3A Principles of ecologically sustainable development

The following principles are principles of ecologically sustainable development:

(a) decision-making processes should effectively integrate both long-term and short-term economic, environmental, social and equitable considerations;

(b) if there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation;

(c) the principle of inter-generational equity—that the present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations;

(d) the conservation of biological diversity and ecological integrity should be a fundamental consideration in decision-making;

(e) improved valuation, pricing and incentive mechanisms should be promoted.

Appendix 2. The GREET model and the SIMAPRO model

The GREET model, available at http://www.transportation.anl.gov/ttrdc/greet/ , or http://greet.anl.gov is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model developed by Michael Q. Wang at Argonne National Laboratories in the United States.

GREET was developed as a multidimensional spreadsheet model in Microsoft Excel. The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model.

For a given engine and fuel system, GREET separately calculates the following:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal), and petroleum
- Emissions of CO_2-equivalent greenhouse gases - primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)
- Emissions of five criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 micron (PM10), and sulfur oxides (SOx).

GREET includes more than 30 fuel-cycle pathways. It also includes these vehicle technologies

- Conventional spark- ignition engines
- Direct-injection, spark- ignition engines
- Direct injection, compression ignition engines
- Grid-connected hybrid electric vehicles
- Grid-independent hybrid electric vehicles
- Battery-powered electric vehicles
- Fuel-cell vehicles.

To address technology improvements over time, GREET separates fuels and vehicle technologies into near- and long-term options. The latter are assumed to have improved energy and emission performance compared with the former.

The version of GREET that is available is GREET 1.5, though a test version of GREET 1.6 was made available on 14 August 2001. In addition there is a heavy vehicle module, known as the GREET 3 series that is designed to estimate fuel-cycle energy use and emissions of heavy-duty trucks and buses. This is not available outside of Argonne.

The GREET model combines spreadsheet calculations with US specific life-cycle data for light vehicles. SIMAPRO was considered to be more suitable for use in the Australian context for the following reasons.

The GREET model is based on US data. Thus, for example, ethanol assumes production from corn, woody biomass and herbaceous biomass not grain and molasses, Biodiesel assumes production from soybean not canola, tallow, waste oil etc. Electricity production includes nuclear power in its assumptions.

The GREET 1 series is designed to estimate fuel-cycle energy use and emissions for passenger cars and utility vehicles only. The GREET 3 series (which is not yet available) is designed to estimate fuel-cycle energy use and emissions of heavy-duty trucks and buses.

In a number of cases Australian practice is sufficiently different (e.g. widespread pipeline transport of CNG) that substantial modification would have been needed to make GREET relevant to Australian conditions.

SIMAPRO has an extensive Australian database of manufacturing energy input and emissions available for it.

SIMAPRO is able to provide embodied energies and exbodied emissions from a greater range of pollutants than GREET presently does.

In the preparation of this report there has been widespread use of the technical information that underlies the GREET model. The work of Wang (1999), Wang and Huang (1999) and Wang et al. (1997, 1999, 2000) was used to estimate values for those input variables or parameters that were not quantified in the Australian database, and to provide a check on our results.

A great advantage of SIMAPRO is its ability to produce process trees. Figure A2.1 indicates a process tree obtained from the SimaPro software used to undertake the quantitative life-cycle components of the study. These trees indicate, in an abbreviated form, the upstream components used to evaluate each component of the life-cycle.

To interpret the process tree, one starts at the top. Thus, in Figure A2.1, the values in the box refer to the mass (in kg) of CO2-equ. To travel 1 km using LSD, there is a total of 0.926 kg emitted, as shown in the top box and summarised in Table 1.21 of Chapter 1 (Part 2). The fuel energy expended in travelling this 1 km is 10.8 MJ, as depicted in the second box down. The box below, which we shall call the fuel box, indicates that prior to combustion, the fuel tank contained 0.251 kg of fuel and that the upstream emissions of CO2-equ to manufacture this fuel amounted to 0.207 kg CO2-eq., as shown in Table 1.22 of Chapter 1 (part 2).

Two separate process trees are depicted below the fuel box. The left hand side shows the upstream emissions involved in refining crude oil to produce diesel fuel. The process tree on the right shows the upstream emissions involved in hydro-processing to reduce the sulfur content of the fuel. For clarity, not all upstream processes are shown. If various upstream processes are not included, this is apparent by examining the bottom of the box. Small lines (tick marks) indicate that the full analysis consists of upstream processes feeding in to that box.

The computer software produces output in colour. On the right of each box there is a green line, with a red lower portion. The red lower proportion represents the proportion of the total value (0.926) accumulated up to that point. This can be seen by carefully examining the fuel box. The bottom 20% of the bar on the right of the box is darker than the remainder. The two top boxes have bars that are completely red.

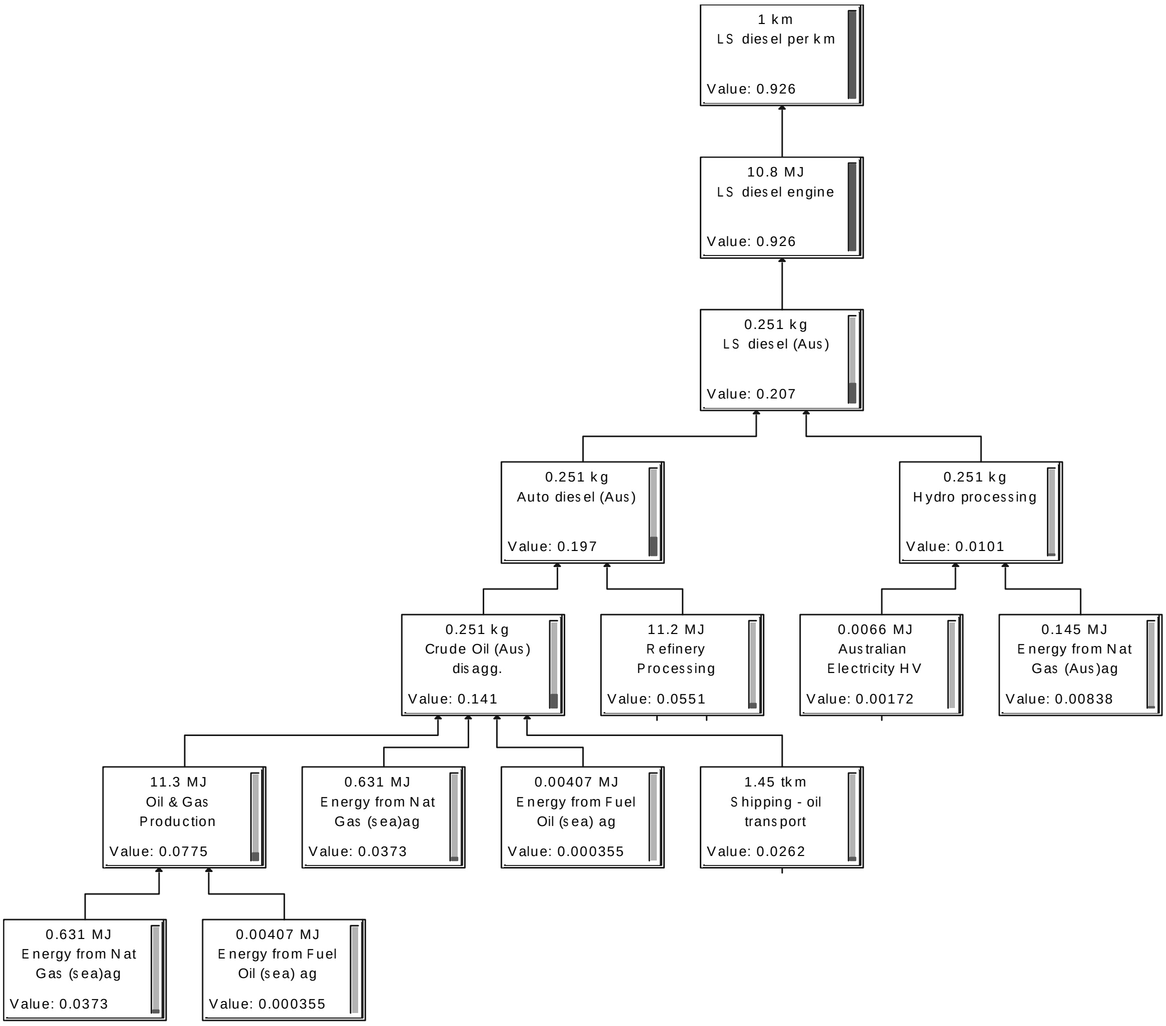

Figure A2.1
Exbodied greenhouse gases emissions (kg CO_2-eq) from LSD production, processing and use in vehicle. The value is given in the bottom of each box.

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Appendix 3 Uncertainty Analysis

An important consideration in the examination of alternative fuels is that most emissions data is highly variable. Thus it is difficult to know, when comparing different fuels, whether observed variations reflect a genuine difference between the two fuels or merely reflect the statistical variability. Beer et al. (2000) stress that this indicates that, wherever possible, comparison between alternative fuels needs to be done on a statistical basis.

Comparing fuels on a statistical basis means that one needs an estimate of both the mean value and the standard deviation of the variable that is being studied. Beer et al. (2000) characterised the uncertainty as the standard deviation divided by the mean value (expressed as a percent). Both these quantities were evaluated on the basis of the measured tailpipe emissions from trucks and buses that Beer et al. (2000) obtained from the US Department of Energy web site.

Tables A3.1 and A3.2 give the percentage uncertainties from Beer et al. (2000). These uncertainties have been reproduced in each chapter of this report, and the uncertainty for the emissions in g/MJ has also been estimated as the average of the two values.

The numerical values of the uncertainties given in Part 2 of the report have been used to determine the uncertainty limits displayed on the bar charts of Part 1 of the report. They also form the basis for the determination of whether fuels are significantly better or worse than the reference fuel, as given in Table 1 of the executive summary.

A3.1 Buses

The uncertainties are tabulated for buses in Table A3.1.

Table A3.1
Uncertainties (in percent) of tailpipe emissions for buses

Fuel	*N*	*f*	CO	THC	NOx	PM	CO_2
BD	11	2.7	37	15	38	61	7
BD20	8	2.3	55		36	50	6
CNG	90	4.6	22	136	72	108	12
Diesel	73	4.4	78	17	27	50	11
E93	6	1.9	66		26	45	7
E95	47	4.0	46	73	35	46	13
LNG	22	3.4	106	11	28	46	8

The smallest uncertainties are associated with CO_2 emissions. This is to be expected because CO_2 can be estimated from fuel usage, which is determined by the engine technology and the mechanical energy required to accomplish the test cycle. The other emissions are trace, unwanted side products. In general, the lowest uncertainties are associated with THC and NOx emissions, and the highest with CO and particulate emissions. The large uncertainties associated with air pollutant emissions from CNG are particularly noticeable. As this fuel is in widespread use in Australian bus fleets, it appears that further analysis is required to reduce the uncertainties associated with CNG emissions and hence enable a more accurate assessment of their air pollution potential.

A3.2 Heavy vehicles other than buses

The uncertainties are tabulated for heavy vehicles other than buses in Table A3.2.

Table A3.2
Uncertainties (in percent) of tailpipe emissions for heavy vehicles other than buses

Fuel	***N***	***f***	**CO**	**THC**	**NOx**	**PM**	**CO_2**
BD	8	2.3	106	71	23	81	15
BD35	12	2.8	49		35	54	39
CNG	7	2.2	11		29	17	2
Diesel	33	3.8	144	50	30	39	9
E95	6	1.9	36	17	8	45	15
LNG	18	3.2	18		47	48	6
LSD	8	2.3	80		9	84	11

Appendix 4 Stakeholder Consultation

Stakeholder consultation was an essential part of the process of undertaking this comparison of transport fuels. In addition to the consultation with the AGO and EA, this took the following forms:

Presentations given by members of the project team on the methodology to be adopted. This meeting took place at the National Gallery of Australia on 7 March 2001, and was organised by the AGO.

Discussions or meetings with individual stakeholders. These included:

Attendance by Dr Tom Beer at the Australian Trucking Association meeting on the Diesel NEPM on 8 March 2001

Telephone conversation with Mr Thomas Carroll of Lubrizol on 14 March 2001 and subsequent receipt of information concerning PuriNOx.

Telephone conversation between Jack Lapszewicz and Bob Gordon of the Australian Biofuels Association on 21 March 2001.

Telephone conversation between Mr John Eisner on 21 March 2001 that was followed up with a face-to-face meeting (in Camberwell) on 4 April 2001 between Tom Beer, Tim Grant, John Eisner (Biofuel manufacturer) and Bob Coutts.

Face-to-face meeting (in Aspendale) on 29 March 2001 between Tom Beer, Lou Daniel (Biofuel manufacturer) and Geoff Peel (Croydon bus lines).

Extensive telephone conversation between Tom Beer and Dr Russell Reeves (APACE, Diesohol manufacturer) on 3 April 2001 and subsequent receipt of information on diesohol emissions. This was followed by a face-to-face meeting at the Tullamarine Qantas Club on 16 April 2001 between Tom Beer, Tim Grant, Russell Reeves and Ernie Lom.

Extensive telephone conversation between Tom Beer and Phillip Calais (Murdoch University, biodiesel researcher) on 5 April 2001 and subsequent receipt of information on biodiesel.

Visit by Tim Grant to Libby Anthony (General Manager of the Alternative Technology Association) on 6 April 2001.

Extensive telephone conversation between Tom Beer and Adrian Lake (Australian Biodiesel Association) on 9 April 2001 and subsequent receipt of e-mails containing information on biodiesel emissions.

Face-to-face meeting (at RMIT) on 11 April 2001 between Tom Beer, Tim Grant and Mark Sanders (BP) concerning low sulfur diesel.

On 7 June 2001 a stakeholders forum was held at CSIRO Atmospheric Research at Aspendale, Vic. The presentations at the forum, along with a list of attendees (reproduced below) are posted on the web at:

http://www.dar.csiro.au/res/ggss/Life%20Cycle%20Analysis%20for%20Alternative%20Fuels.htm

As a result of the forum it was decided to have further consultation in the form of focussed roundtable meetings that were held at RMIT in Melbourne. On 25 June meetings were held with the biofuels stakeholders in the morning, and with the gaseous fuels stakeholders in the afternoon. On the morning of 26 June a meeting was held with the remaining stakeholders.

The forum and roundtables generated considerable further information that was incorporated into the study.

Attendees at
Comparison of Transport Fuel Stakeholders Forum
7 June 2001,
CSIRO Atmospheric Research

Tom Beer CSIRO Atmospheric Research	Ian Galbally CSIRO Atmospheric Research
Roger Coogan Australian Greenhouse Office	Jane Sellenger CSIRO Atmospheric Research
Peter Anyon PARSONS	Harry Watson University of Melbourne
Peter Nelson CSIRO Energy Technology	Jim Edwards CSIRO Energy Technology
Tim Grant R.M.I.T.	Chris Mitchell CSIRO Atmospheric Research
Janine Cullen Australian Greenhouse Office	Darren Sanford Biodiesel Power
Vicki Ratliffe Environment Australia	Kate Gainer Environment Australia
Paul Martin Biodiesel Association	Darryl Butcher Amadeus Petroleum NL
Rod Jones Wesfarmers Kleenheat	Horst Koerner Scania Australia Pty Ltd
Mark Morarty Toyota Motor Corp. Australia (TMCA)	Geoff Peel Croydon Bus Service Pty Ltd
Phil Stirling FCAI (Holden)	Tracey Winters Sasol Chevron
Robin Davies Origin Energy	Rod James Wesfarmers Kleenheat
Stewart McDonald Ford Motor Company of Australia	Tony Moleta Dept of Transport and Regional Services
Sanjay Chatterjee	Jim Le Cornu Shell Australia
Ian Bridgland Shell Australia	
Michael Apps Australian Trucking Association	Warring Neilsen Elgas
Sheryll Fisher Urban Energy Pty Ltd	Ewan MacPherson Australian Institute of Petroleum
Henry O'Clery Greenfleet	Brett Jarman ANGVC
Sean Blythe ANGVC	Phillip Westlake Australian LP Gas Association Ltd
Kerrie Hepworth Australian Taxation Office (ATO)	Yuanfang Shen Australian Taxation Office (ATO)
John Eisner Equinox Management Pty Ltd	Max Blamey Australian Taxation Office (ATO)
Peter Nimmo Queensland EPA	Kerry Lack NSW EPA
Stuart Ballingal RACV	Kevin Black NGV Solutions Pty Ltd

David Graham Daimler Chrysler	John Bortolussi Cummins
Terry Green Cummins	Paul Harrison Advanced Fuels Technology Pty Ltd
Damien Tangey Dipetane Australia	Kym Godson Clean Fuels Technology Inc.
Hien Ly Agility Management	Elliott Curley Agriculture, Fisheries and Forestry - Australia
Adrian Lake Biodiesel Association of Australia Inc	Steve Isles RTA
David Kernich Transport SA	Glenn Cooper IMPCO Technologies
Peter Wrigley Vicol Petroleum Pty Ltd	Terry Shulze Biodiesel
Kathryn Hannan RACV	Mark Dess Dept Natural Resources & Environment
Rowena Main Department of Infracture, ODPT	Deb Wilkinson Senator Allisons Office
Guy Macklan Detroit Diesel	Ros Pyett Department of Transport and Regional Services
Mark Sanders BP Australia	Frank Russell BP Australia
Chris Russell Elgas	Fred Goede Sasol Chevron
David Liversidge Australian Greenhouse Office	Ernie Lom Apace Research Ltd
Scott McDowall Queensland EPA	Matthew Minchin EPA Victoria
Luke Hardy State Transit Authority	Tony Sharp State Transit Authority

In addition, input was also sought from the following organizations that were unable to attend the stakeholder forum:

National Environment Consultative Forum
Australian Trucking Association
Bus Industry Confederation
Federal Chamber Automotive Industries
Australian Institute of Petroleum
Australian Automobile Association

The following Government departments were consulted:

- Agriculture Fisheries and Forestries Australia
- Australian Bureau of Agricultural Research Economics
- Australian Taxation Office
- Environment Australia
- Department of Health and Aged Care
- Department of Industry Science and Resources
- Department of Transport and Regional Services
- Department of Treasury

Motor Vehicle Environment Committee members

National Environment Protection Committee
National Road Transport Commission

Appendix 5 Emissions of pollutants per tonne-kilometre and per passenger-kilometre

Emissions per tonne-kilometre

Table A5.1

Urban and rural life cycle emissions

Full Lifecycle	**Units**	**LS diesel (Aus)**	**ULS diesel (Aus)**	**ULS diesel (100% hydroprocessing)**	**Fischer-Tropsch diesel**
Greenhouse	kg CO2	0.1030	0.1055	0.1032	0.1105
NMHC total	g HC	0.168	0.152	0.150	0.105
NMHC urban	g HC	0.133	0.115	0.114	0.058
NOx total	g NOx	1.253	1.102	1.086	1.147
NOx urban	g NOx	1.185	1.033	1.017	0.991
CO total	g CO	0.303	0.379	0.376	0.260
CO urban	g CO	0.291	0.367	0.363	0.224
PM10 total	mg PM10	48.8	38.3	38.2	29.6
PM10 urban	mg PM10	47.1	36.6	36.5	27.5
Energy Embodied	MJ LHV	1.41	1.46	1.44	1.90

Full Lifecycle	**Units**	**LS diesel (Aus)**	**Biodiesel (canola)**	**Biodiesel (soybean)**	**Biodiesel (rape)**	**Biodiesel (tallow-expanded sys. boundary)**	**Biodiesel (tallow-eco.allocat.)**	**Biodiesel (waste oil)**	**Biodiesel (waste oil 10% original oil value)**
Greenhouse	kg CO2	0.1030	0.0480	0.0362	0.0491	0.0465	0.0552	0.0079	0.0082
NMHC total	g HC	0.168	0.160	0.190	0.161	0.157	0.067	0.066	0.068
NMHC urban	g HC	0.133	0.148	0.180	0.148	0.145	0.065	0.065	0.066
NOx total	g NOx	1.253	1.436	1.423	1.456	1.431	1.312	1.310	1.316
NOx urban	g NOx	1.185	1.350	1.369	1.352	1.349	1.311	1.309	1.315
CO total	g CO	0.303	0.189	0.243	0.190	0.188	0.157	0.156	0.161
CO urban	g CO	0.291	0.172	0.232	0.172	0.171	0.156	0.156	0.161
PM10 total	mg PM10	48.8	33.1	32.6	33.8	33.0	30.6	30.5	30.5
PM10 urban	mg PM10	47.1	31.5	31.5	31.5	31.4	30.6	30.5	30.5
Energy Embodied	MJ LHV	1.41	0.46	0.50	0.47	0.45	0.19	0.18	0.18

Full Lifecycle	**Units**	**LS diesel (Aus)**	**CNG (Electric compression)**	**CNG (NG compression)**	**LNG (from existing transmission line)**	**LNG (Shipped from north west shelf)**	**LNG (perth)**	**LPG (Autogas)**	**LPG (HD5)**
Greenhouse	kg CO2	0.1030	0.0852	0.0874	0.0833	0.0841	0.0873	0.0930	0.0998
NMHC total	g HC	0.168	0.034	0.037	0.035	0.035	0.038	0.123	0.126
NMHC urban	g HC	0.133	0.003	0.004	0.003	0.002	0.004	0.091	0.092
NOx total	g NOx	1.253	0.179	0.195	0.258	0.260	0.305	0.170	0.503
NOx urban	g NOx	1.185	0.162	0.176	0.240	0.221	0.225	0.108	0.439
CO total	g CO	0.303	0.014	0.018	0.015	0.016	0.017	0.046	0.043
CO urban	g CO	0.291	0.006	0.010	0.007	0.004	0.005	0.035	0.032
PM10 total	mg PM10	48.8	8.4	8.5	8.2	8.3	10.4	10.8	7.9
PM10 urban	mg PM10	47.1	8.2	8.3	8.0	7.8	8.0	9.2	6.3
Energy Embodied	MJ LHV	1.41	1.39	1.46	1.39	1.40	1.44	1.29	1.33

Table A5.1 (cont).

Urban and rural life cycle emissions

Full Lifecycle	**Units**	**LS diesel (Aus)**	**LSdiesohol**	**Ethanol azeotropic (molasses-expanded sys.bound.)**	**Ethanol azeotropic (molasses-economic allocation)**	**Ethanol azeotropic (wheat starch waste)**	**Ethanol azeotropic (wheat)**	**Ethanol azeotropic (wheat) fired with wheat straw**	**Ethanol azeotropic (woodwaste)**	**Ethanol azeotropic (ethylene)**	**Hydrogen (from natural gas)**
Greenhouse	kg CO2	0.1030	0.0960	0.0483	0.0838	0.0425	0.0769	0.0383	0.0092	0.1636	0.1852
NMHC total	g HC	0.168	0.159	0.096	0.095	0.086	0.162	1.116	0.720	0.743	0.179
NMHC urban	g HC	0.133	0.127	0.092	0.093	0.084	0.092	1.046	0.719	0.656	0.140
NOx total	g NOx	1.253	1.158	1.116	1.115	1.083	1.311	1.249	1.032	1.351	0.172
NOx urban	g NOx	1.185	1.094	1.080	1.109	1.080	1.118	1.057	1.030	1.302	0.151
CO total	g CO	0.303	0.402	1.010	1.194	0.363	1.258	4.303	2.543	0.427	1.105
CO urban	g CO	0.291	0.390	1.003	1.192	0.362	0.366	3.412	2.543	0.407	1.096
PM10 total	mg PM10	48.8	38.1	32.8	32.1	56.1	60.1	83.0	62.2	37.7	40.5
PM10 urban	mg PM10	47.1	36.5	32.1	31.9	56.0	56.9	79.7	62.1	37.0	40.2
Energy Embodied	MJ LHV	1.41	1.33	0.49	0.56	0.50	0.79	0.92	3.14	4.03	1.69

Table A5.2

Urban and rural upstream emissions

Precombustion	**Units**	**LS diesel (Aus)**	**ULS diesel (Aus)**	**ULS diesel (100% hydroprocessing)**	**Fischer-Tropsch diesel**
Greenhouse	kg CO2	0.0229	0.026	0.023	0.036
NMHC total	g HC	0.068	0.070	0.069	0.047
NMHC urban	g HC	0.033	0.034	0.033	0.001
NOx total	g NOx	0.120	0.138	0.121	0.163
NOx urban	g NOx	0.052	0.068	0.053	0.006
CO total	g CO	0.027	0.031	0.027	0.037
CO urban	g CO	0.015	0.018	0.015	0.001
PM10 total	mg PM10	6.503	6.704	6.581	2.260
PM10 urban	mg PM10	4.799	4.966	4.855	0.082
Energy Embodied	MJ LHV	1.414	1.459	1.436	1.904

Precombustion	**Units**	**LS diesel (Aus)**	**Biodiesel (canola)**	**Biodiesel (soybean)**	**Biodiesel (rape)**	**Biodiesel (tallow-expanded sys. boundary)**	**Biodiesel (tallow-eco.allocat.)**	**Biodiesel (waste oil)**	**Biodiesel (waste oil 10% original oil value)**
Greenhouse	kg CO2	0.0229	0.048	0.036	0.049	0.047	0.055	0.008	0.008
NMHC total	g HC	0.068	0.156	0.186	0.157	0.153	0.062	0.062	0.063
NMHC urban	g HC	0.033	0.144	0.176	0.144	0.140	0.061	0.061	0.062
NOx total	g NOx	0.120	0.155	0.141	0.175	0.150	0.031	0.029	0.034
NOx urban	g NOx	0.052	0.069	0.088	0.071	0.068	0.030	0.028	0.034
CO total	g CO	0.027	0.038	0.092	0.039	0.037	0.006	0.005	0.010
CO urban	g CO	0.015	0.021	0.082	0.021	0.020	0.005	0.005	0.010
PM10 total	mg PM10	6.503	2.784	2.216	3.463	2.695	0.242	0.208	0.208
PM10 urban	mg PM10	4.799	1.125	1.180	1.158	1.088	0.228	0.196	0.196
Energy Embodied	MJ LHV	1.414	0.461	0.501	0.473	0.451	0.188	0.179	0.184

Table A5.2 (cont).

Urban and rural upstream emissions

Precombustion	Units	LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	kg CO2	0.0229	0.015	0.017	0.014	0.015	0.018	0.021	0.021
NMHC total	g HC	0.068	0.032	0.035	0.033	0.033	0.036	0.122	0.124
NMHC urban	g HC	0.033	0.001	0.001	0.001	0.000	0.002	0.090	0.090
NOx total	g NOx	0.120	0.034	0.049	0.037	0.039	0.084	0.111	0.110
NOx urban	g NOx	0.052	0.016	0.030	0.019	0.000	0.004	0.049	0.046
CO total	g CO	0.027	0.009	0.014	0.011	0.012	0.013	0.025	0.025
CO urban	g CO	0.015	0.002	0.006	0.004	0.000	0.001	0.014	0.013
PM10 total	mg PM10	6.503	0.562	0.673	0.506	0.534	2.706	6.459	6.136
PM10 urban	mg PM10	4.799	0.329	0.420	0.263	0.008	0.263	4.888	4.532
Energy Embodied	MJ LHV	1.414	1.391	1.462	1.392	1.403	1.436	1.292	1.325

Precombustion	Units	LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	kg CO2	0.0229	0.026	0.048	0.084	0.043	0.077	0.038	0.009	0.115	0.100
NMHC total	g HC	0.068	0.064	0.015	0.013	0.004	0.080	1.034	0.638	0.661	0.040
NMHC urban	g HC	0.033	0.032	0.010	0.011	0.003	0.011	0.964	0.637	0.575	0.001
NOx total	g NOx	0.120	0.124	0.148	0.147	0.116	0.343	0.282	0.065	0.383	0.063
NOx urban	g NOx	0.052	0.059	0.112	0.141	0.112	0.150	0.090	0.062	0.334	0.041
CO total	g CO	0.027	0.090	0.660	0.844	0.013	0.909	3.953	2.194	0.077	0.015
CO urban	g CO	0.015	0.078	0.654	0.842	0.012	0.016	3.062	2.194	0.057	0.005
PM10 total	mg PM10	6.503	5.957	1.058	0.340	24.387	28.395	51.223	30.511	5.924	0.811
PM10 urban	mg PM10	4.799	4.354	0.357	0.214	24.275	25.166	47.994	30.400	5.267	0.521
Energy Embodied	MJ LHV	1.414	1.325	0.491	0.561	0.504	0.790	0.920	3.140	4.031	1.693

Table A5.3

Urban and rural tailpipe emissions

Combustion	Units	LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	kg CO2	0.080	0.080	0.080	0.075
NMHC total	g HC	0.100	0.081	0.081	0.057
NMHC urban	g HC	0.100	0.081	0.081	0.057
NOx total	g NOx	1.132	0.964	0.964	0.985
NOx urban	g NOx	1.132	0.964	0.964	0.985
CO total	g CO	0.276	0.349	0.349	0.223
CO urban	g CO	0.276	0.349	0.349	0.223
PM10 total	mg PM10	42.31	31.62	31.62	27.38
PM10 urban	mg PM10	42.31	31.62	31.62	27.38
Energy Embodied	MJ LHV	0	0	0	0

Table A5.3 (cont.)

Urban and rural tailpipe emissions

Combustion	Units	LS diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow-expanded sys. boundary)	Biodiesel (tallow-eco.allocat.)	Biodiesel (waste oil)	Biodiesel (waste oil 10% original oil value)
Greenhouse	kg CO2	0.080	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NMHC total	g HC	0.100	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NMHC urban	g HC	0.100	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NOx total	g NOx	1.132	1.281	1.281	1.281	1.281	1.281	1.281	1.281
NOx urban	g NOx	1.132	1.281	1.281	1.281	1.281	1.281	1.281	1.281
CO total	g CO	0.276	0.151	0.151	0.151	0.151	0.151	0.151	0.151
CO urban	g CO	0.276	0.151	0.151	0.151	0.151	0.151	0.151	0.151
PM10 total	mg PM10	42.31	30.34	30.34	30.34	30.34	30.34	30.34	30.34
PM10 urban	mg PM10	42.31	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0

Combustion	Units	LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	kg CO2	0.080	0.070	0.070	0.069	0.069	0.069	0.072	0.079
NMHC total	g HC	0.100	0.002	0.002	0.002	0.002	0.002	0.001	0.003
NMHC urban	g HC	0.100	0.002	0.002	0.002	0.002	0.002	0.001	0.003
NOx total	g NOx	1.132	0.146	0.146	0.221	0.221	0.221	0.059	0.393
NOx urban	g NOx	1.132	0.146	0.146	0.221	0.221	0.221	0.059	0.393
CO total	g CO	0.276	0.004	0.004	0.004	0.004	0.004	0.021	0.018
CO urban	g CO	0.276	0.004	0.004	0.004	0.004	0.004	0.021	0.018
PM10 total	mg PM10	42.31	7.85	7.85	7.74	7.74	7.74	4.31	1.74
PM10 urban	mg PM10	42.31	7.85	7.85	7.74	7.74	7.74	4.31	1.74
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0

Combustion	Units	LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	kg CO2	0.080	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.049	0.085
NMHC total	g HC	0.100	0.095	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.139
NMHC urban	g HC	0.100	0.095	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.139
NOx total	g NOx	1.132	1.035	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.109
NOx urban	g NOx	1.132	1.035	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.109
CO total	g CO	0.276	0.312	0.350	0.350	0.350	0.350	0.350	0.350	0.350	1.091
CO urban	g CO	0.276	0.312	0.350	0.350	0.350	0.350	0.350	0.350	0.350	1.091
PM10 total	mg PM10	42.31	32.16	31.73	31.73	31.73	31.73	31.73	31.73	31.73	39.67
PM10 urban	mg PM10	42.31	32.16	31.73	31.73	31.73	31.73	31.73	31.73	31.73	39.67
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0	0	0

Table 2.4

Summary of life cycle emissions from alternative fuels

		LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	Precombustion	0.0229	0.0255	0.0233	0.0359
Greenhouse	Combustion	0.0801	0.0800	0.0800	0.0747
NMHC total	Precombustion	0.0678	0.0705	0.0686	0.0473
NMHC total	Combustion	0.1002	0.0813	0.0813	0.0574
NMHC urban	Precombustion	0.0325	0.0341	0.0330	0.0010
NMHC urban	Combustion	0.1002	0.0813	0.0813	0.0574
NOx total	Precombustion	0.1203	0.1381	0.1214	0.1626
NOx total	Combustion	1.132	0.964	0.964	0.985
NOx urban	Precombustion	0.052	0.068	0.053	0.006
NOx urban	Combustion	1.132	0.964	0.964	0.985
CO total	Precombustion	0.0271	0.0310	0.0274	0.0370
CO total	Combustion	0.2761	0.3485	0.3485	0.2228
CO urban	Precombustion	0.0147	0.0183	0.0149	0.0010
CO urban	Combustion	0.2761	0.3485	0.3485	0.2228
PM10 total	Precombustion	6.50	6.70	6.58	2.26
PM10 total	Combustion	42.31	31.62	31.62	27.38
PM10 urban	Precombustion	4.80	4.97	4.86	0.08
PM10 urban	Combustion	42.31	31.62	31.62	27.38
Energy Embodied	Precombustion	1.41	1.46	1.44	1.90

		LS diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow-expanded sys. boundary)	Biodiesel (tallow-eco.allocat.)	Biodiesel (waste oil)	Biodiesel (waste oil 10% original oil value)
Greenhouse	Precombustion	0.0229	0.048	0.036	0.049	0.047	0.055	0.008	0.008
Greenhouse	Combustion	0.0801	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NMHC total	Precombustion	0.0678	0.156	0.186	0.157	0.153	0.062	0.062	0.063
NMHC total	Combustion	0.1002	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NMHC urban	Precombustion	0.0325	0.144	0.176	0.144	0.140	0.061	0.061	0.062
NMHC urban	Combustion	0.1002	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NOx total	Precombustion	0.1203	0.155	0.141	0.175	0.150	0.031	0.029	0.034
NOx total	Combustion	1.132	1.281	1.281	1.281	1.281	1.281	1.281	1.281
NOx urban	Precombustion	0.052	0.069	0.088	0.071	0.068	0.030	0.028	0.034
NOx urban	Combustion	1.132	1.281	1.281	1.281	1.281	1.281	1.281	1.281
CO total	Precombustion	0.0271	0.038	0.092	0.039	0.037	0.006	0.005	0.010
CO total	Combustion	0.2761	0.151	0.151	0.151	0.151	0.151	0.151	0.151
CO urban	Precombustion	0.0147	0.021	0.082	0.021	0.020	0.005	0.005	0.010
CO urban	Combustion	0.2761	0.151	0.151	0.151	0.151	0.151	0.151	0.151
PM10 total	Precombustion	6.50	2.784	2.216	3.463	2.695	0.242	0.208	0.208
PM10 total	Combustion	42.31	30.339	30.339	30.339	30.339	30.339	30.339	30.339
PM10 urban	Precombustion	4.80	1.125	1.180	1.158	1.088	0.228	0.196	0.196
PM10 urban	Combustion	42.31	30.339	30.339	30.339	30.339	30.339	30.339	30.339
Energy Embodied	Precombustion	1.41	0.461	0.501	0.473	0.451	0.188	0.179	0.184

Table A5.4 (cont.)

Summary of life cycle emissions from alternative fuels

		LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	Precombustion	0.0229	0.0151	0.0173	0.0143	0.0150	0.0183	0.0207	0.0207
Greenhouse	Combustion	0.0801	0.0701	0.0701	0.0690	0.0690	0.0690	0.0723	0.0791
NMHC total	Precombustion	0.0678	0.0318	0.0350	0.0332	0.0332	0.0359	0.1225	0.1236
NMHC total	Combustion	0.1002	0.0025	0.0025	0.0020	0.0020	0.0020	0.0009	0.0026
NMHC urban	Precombustion	0.0325	0.0008	0.0013	0.0010	0.0001	0.0015	0.0903	0.0899
NMHC urban	Combustion	0.1002	0.0025	0.0025	0.0020	0.0020	0.0020	0.0009	0.0026
NOx total	Precombustion	0.1203	0.0336	0.0492	0.0371	0.0391	0.0843	0.1114	0.1100
NOx total	Combustion	1.132	0.146	0.146	0.221	0.221	0.221	0.059	0.393
NOx urban	Precombustion	0.052	0.016	0.030	0.019	0.000	0.004	0.049	0.046
NOx urban	Combustion	1.132	0.146	0.146	0.221	0.221	0.221	0.059	0.393
CO total	Precombustion	0.0271	0.0092	0.0138	0.0112	0.0117	0.0135	0.0254	0.0249
CO total	Combustion	0.2761	0.0043	0.0043	0.0039	0.0039	0.0039	0.0208	0.0185
CO urban	Precombustion	0.0147	0.0018	0.0057	0.0036	0.0001	0.0011	0.0140	0.0134
CO urban	Combustion	0.2761	0.0043	0.0043	0.0039	0.0039	0.0039	0.0208	0.0185
PM10 total	Precombustion	6.50	0.56	0.67	0.51	0.53	2.71	6.46	6.14
PM10 total	Combustion	42.31	7.85	7.85	7.74	7.74	7.74	4.31	1.74
PM10 urban	Precombustion	4.80	0.33	0.42	0.26	0.01	0.26	4.89	4.53
PM10 urban	Combustion	42.31	7.85	7.85	7.74	7.74	7.74	4.31	1.74
Energy Embodied	Precombustion	1.41	1.39	1.46	1.39	1.40	1.44	1.29	1.33

		LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	Precombustion	0.0229	0.0257	0.0483	0.0838	0.0425	0.0769	0.0383	0.0092	0.1147	0.0999
Greenhouse	Combustion	0.0801	0.0703	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0489	0.0853
NMHC total	Precombustion	0.0678	0.0638	0.0148	0.0131	0.0044	0.0802	1.0345	0.6381	0.6614	0.0399
NMHC total	Combustion	0.1002	0.0954	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.1388
NMHC urban	Precombustion	0.0325	0.0316	0.0105	0.0114	0.0027	0.0109	0.9643	0.6369	0.5746	0.0013
NMHC urban	Combustion	0.1002	0.0954	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.1388
NOx total	Precombustion	0.1203	0.1236	0.1481	0.1470	0.1158	0.3430	0.2817	0.0646	0.3831	0.0632
NOx total	Combustion	1.132	1.035	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.109
NOx urban	Precombustion	0.052	0.059	0.112	0.141	0.112	0.150	0.090	0.062	0.334	0.041
NOx urban	Combustion	1.132	1.035	0.968	0.968	0.968	0.968	0.968	0.968	0.968	0.109
CO total	Precombustion	0.0271	0.0896	0.6603	0.8441	0.0128	0.9086	3.9531	2.1937	0.0773	0.0146
CO total	Combustion	0.2761	0.3119	0.3498	0.3498	0.3498	0.3498	0.3498	0.3498	0.3498	1.0909
CO urban	Precombustion	0.0147	0.0779	0.6536	0.8418	0.0121	0.0165	3.0622	2.1937	0.0568	0.0055
CO urban	Combustion	0.2761	0.3119	0.3498	0.3498	0.3498	0.3498	0.3498	0.3498	0.3498	1.0909
PM10 total	Precombustion	6.50	5.96	1.06	0.34	24.39	28.40	51.22	30.51	5.92	0.81
PM10 total	Combustion	42.31	32.16	31.73	31.73	31.73	31.73	31.73	31.73	31.73	39.67
PM10 urban	Precombustion	4.80	4.35	0.36	0.21	24.28	25.17	47.99	30.40	5.27	0.52
PM10 urban	Combustion	42.31	32.16	31.73	31.73	31.73	31.73	31.73	31.73	31.73	39.67
Energy Embodied	Precombustion	1.41	1.33	0.49	0.56	0.50	0.79	0.92	3.14	4.03	1.69

Emissions per passenger kilometre

Table A5.5

Urban and rural exbodied emissions

Precombustion	Units	LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	kg CO2	0.0910	0.0931	0.0912	0.0976
NMHC total	g HC	0.148	0.134	0.132	0.092
NMHC urban	g HC	0.117	0.102	0.101	0.052
NOx total	g NOx	1.107	0.974	0.959	1.014
NOx urban	g NOx	1.046	0.912	0.898	0.875
CO total	g CO	0.268	0.335	0.332	0.229
CO urban	g CO	0.257	0.324	0.321	0.198
PM10 total	mg PM10	43.1	33.9	33.7	26.2
PM10 urban	mg PM10	41.6	32.3	32.2	24.3
Energy Embodied	MJ LHV	1.249	1.289	1.269	1.682

Precombustion	Units	LS diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow-expanded sys. boundary)	Biodiesel (tallow-eco.allocat.)	Biodiesel (waste oil)	Biodiesel (waste oil 10% original oil value)
Greenhouse	kg CO2	0.0910	0.0424	0.0320	0.0434	0.0411	0.0488	0.0069	0.0072
NMHC total	g HC	0.148	0.142	0.168	0.143	0.139	0.059	0.059	0.060
NMHC urban	g HC	0.117	0.131	0.159	0.131	0.128	0.058	0.058	0.059
NOx total	g NOx	1.107	1.268	1.257	1.286	1.264	1.159	1.157	1.162
NOx urban	g NOx	1.046	1.193	1.209	1.195	1.191	1.158	1.156	1.161
CO total	g CO	0.268	0.167	0.215	0.168	0.166	0.138	0.138	0.143
CO urban	g CO	0.257	0.152	0.205	0.152	0.151	0.138	0.138	0.142
PM10 total	mg PM10	43.1	29.3	28.8	29.9	29.2	27.0	27.0	27.0
PM10 urban	mg PM10	41.6	27.8	27.8	27.8	27.8	27.0	27.0	27.0
Energy Embodied	MJ LHV	1.249	0.407	0.443	0.418	0.398	0.166	0.158	0.162

Precombustion	Units	LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	kg CO2	0.0910	0.0752	0.0772	0.0736	0.0743	0.0771	0.0822	0.0882
NMHC total	g HC	0.148	0.030	0.033	0.031	0.031	0.033	0.109	0.111
NMHC urban	g HC	0.117	0.003	0.003	0.003	0.002	0.003	0.081	0.082
NOx total	g NOx	1.107	0.158	0.172	0.228	0.230	0.270	0.150	0.444
NOx urban	g NOx	1.046	0.143	0.155	0.212	0.196	0.198	0.095	0.387
CO total	g CO	0.268	0.012	0.016	0.013	0.014	0.015	0.041	0.038
CO urban	g CO	0.257	0.005	0.009	0.007	0.003	0.004	0.031	0.028
PM10 total	mg PM10	43.1	7.4	7.5	7.3	7.3	9.2	9.5	7.0
PM10 urban	mg PM10	41.6	7.2	7.3	7.1	6.8	7.1	8.1	5.5
Energy Embodied	MJ LHV	1.249	1.229	1.291	1.230	1.239	1.269	1.141	1.171

Table A5.5 (cont.)

Urban and rural exbodied emissions

Precombustion	Units	LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	kg CO2	0.0910	0.0848	0.0427	0.0741	0.0376	0.0680	0.0338	0.0081	0.1445	0.1636
NMHC total	g HC	0.148	0.141	0.085	0.084	0.076	0.143	0.986	0.636	0.656	0.158
NMHC urban	g HC	0.117	0.112	0.081	0.082	0.074	0.082	0.924	0.635	0.580	0.124
NOx total	g NOx	1.107	1.023	0.986	0.985	0.957	1.158	1.104	0.912	1.193	0.152
NOx urban	g NOx	1.046	0.966	0.954	0.980	0.954	0.988	0.934	0.909	1.150	0.133
CO total	g CO	0.268	0.355	0.892	1.055	0.320	1.112	3.801	2.247	0.377	0.976
CO urban	g CO	0.257	0.344	0.886	1.053	0.320	0.324	3.014	2.247	0.359	0.968
PM10 total	mg PM10	43.1	33.7	29.0	28.3	49.6	53.1	73.3	55.0	33.3	35.8
PM10 urban	mg PM10	41.6	32.3	28.3	28.2	49.5	50.3	70.4	54.9	32.7	35.5
Energy Embodied	MJ LHV	1.249	1.171	0.434	0.496	0.446	0.697	0.812	2.774	3.561	1.495

Table A5.6

Urban and rural upstream emissions

Precombustion	Units	LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	kg CO2	0.020	0.023	0.021	0.032
NMHC total	g HC	0.060	0.062	0.061	0.042
NMHC urban	g HC	0.029	0.030	0.029	0.001
NOx total	g NOx	0.106	0.122	0.107	0.144
NOx urban	g NOx	0.046	0.060	0.047	0.005
CO total	g CO	0.024	0.027	0.024	0.033
CO urban	g CO	0.013	0.016	0.013	0.001
PM10 total	mg PM10	5.744	5.921	5.813	1.997
PM10 urban	mg PM10	4.239	4.387	4.289	0.072
Energy Embodied	MJ LHV	1.249	1.289	1.269	1.682

Precombustion	Units	LS diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow-expanded sys. boundary)	Biodiesel (tallow-eco.allocat.)	Biodiesel (waste oil)	Biodiesel (waste oil 10% original oil value)
Greenhouse	kg CO2	0.020	0.042	0.032	0.043	0.041	0.049	0.007	0.007
NMHC total	g HC	0.060	0.138	0.164	0.139	0.135	0.055	0.055	0.056
NMHC urban	g HC	0.029	0.127	0.155	0.127	0.124	0.054	0.054	0.055
NOx total	g NOx	0.106	0.137	0.125	0.154	0.133	0.027	0.025	0.030
NOx urban	g NOx	0.046	0.061	0.077	0.063	0.060	0.027	0.025	0.030
CO total	g CO	0.024	0.034	0.081	0.035	0.033	0.005	0.005	0.009
CO urban	g CO	0.013	0.019	0.072	0.019	0.018	0.005	0.004	0.009
PM10 total	mg PM10	5.744	2.459	1.957	3.059	2.380	0.213	0.184	0.184
PM10 urban	mg PM10	4.239	0.993	1.043	1.023	0.961	0.202	0.173	0.173
Energy Embodied	MJ LHV	1.249	0.407	0.443	0.418	0.398	0.166	0.158	0.162

Table A5.6 (cont.)

Urban and rural upstream emissions

Precombustion	Units	LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	kg CO2	0.020	0.013	0.015	0.013	0.013	0.016	0.018	0.018
NMHC total	g HC	0.060	0.028	0.031	0.029	0.029	0.032	0.108	0.109
NMHC urban	g HC	0.029	0.001	0.001	0.001	0.000	0.001	0.080	0.079
NOx total	g NOx	0.106	0.030	0.043	0.033	0.035	0.074	0.098	0.097
NOx urban	g NOx	0.046	0.014	0.027	0.017	0.000	0.003	0.043	0.040
CO total	g CO	0.024	0.008	0.012	0.010	0.010	0.012	0.022	0.022
CO urban	g CO	0.013	0.002	0.005	0.003	0.000	0.001	0.012	0.012
PM10 total	mg PM10	5.744	0.497	0.595	0.447	0.472	2.390	5.705	5.420
PM10 urban	mg PM10	4.239	0.290	0.371	0.232	0.007	0.232	4.318	4.003
Energy Embodied	MJ LHV	1.249	1.229	1.291	1.230	1.239	1.269	1.141	1.171

Precombustion	Units	LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	kg CO2	0.020	0.023	0.043	0.074	0.038	0.068	0.034	0.008	0.101	0.088
NMHC total	g HC	0.060	0.056	0.013	0.012	0.004	0.071	0.914	0.564	0.584	0.035
NMHC urban	g HC	0.029	0.028	0.009	0.010	0.002	0.010	0.852	0.563	0.508	0.001
NOx total	g NOx	0.106	0.109	0.131	0.130	0.102	0.303	0.249	0.057	0.338	0.056
NOx urban	g NOx	0.046	0.052	0.099	0.125	0.099	0.133	0.079	0.055	0.295	0.037
CO total	g CO	0.024	0.079	0.583	0.746	0.011	0.803	3.492	1.938	0.068	0.013
CO urban	g CO	0.013	0.069	0.577	0.744	0.011	0.015	2.705	1.938	0.050	0.005
PM10 total	mg PM10	5.744	5.262	0.934	0.300	21.541	25.083	45.247	26.951	5.233	0.716
PM10 urban	mg PM10	4.239	3.846	0.316	0.189	21.443	22.230	42.394	26.853	4.653	0.460
Energy Embodied	MJ LHV	1.249	1.171	0.434	0.496	0.446	0.697	0.812	2.774	3.561	1.495

Table A5.7

Urban and rural tailpipe emissions

Combustion	Units	LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	kg CO2	0.071	0.071	0.071	0.066
NMHC total	g HC	0.089	0.072	0.072	0.051
NMHC urban	g HC	0.089	0.072	0.072	0.051
NOx total	g NOx	1.000	0.852	0.852	0.870
NOx urban	g NOx	1.000	0.852	0.852	0.870
CO total	g CO	0.244	0.308	0.308	0.197
CO urban	g CO	0.244	0.308	0.308	0.197
PM10 total	mg PM10	37.38	27.94	27.94	24.18
PM10 urban	mg PM10	37.38	27.94	27.94	24.18
Energy Embodied	MJ LHV	0	0	0	0

Table A5.7 (cont.)

Urban and rural tailpipe emissions

Combustion	**Units**	**LS diesel (Aus)**	**Biodiesel (canola)**	**Biodiesel (soybean)**	**Biodiesel (rape)**	**Biodiesel (tallow-expanded sys. boundary)**	**Biodiesel (tallow-eco.allocat.)**	**Biodiesel (waste oil)**	**Biodiesel (waste oil 10% original oil value)**
Greenhouse	kg CO2	0.071	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NMHC total	g HC	0.089	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NMHC urban	g HC	0.089	0.004	0.004	0.004	0.004	0.004	0.004	0.004
NOx total	g NOx	1.000	1.132	1.132	1.132	1.132	1.132	1.132	1.132
NOx urban	g NOx	1.000	1.132	1.132	1.132	1.132	1.132	1.132	1.132
CO total	g CO	0.244	0.133	0.133	0.133	0.133	0.133	0.133	0.133
CO urban	g CO	0.244	0.133	0.133	0.133	0.133	0.133	0.133	0.133
PM10 total	mg PM10	37.38	26.80	26.80	26.80	26.80	26.80	26.80	26.80
PM10 urban	mg PM10	37.38	26.80	26.80	26.80	26.80	26.80	26.80	26.80
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0

Combustion	**Units**	**LS diesel (Aus)**	**CNG (Electric compression)**	**CNG (NG compression)**	**LNG (from existing transmission line)**	**LNG (Shipped from north west shelf)**	**LNG (perth)**	**LPG (Autogas)**	**LPG (HD5)**
Greenhouse	kg CO2	0.071	0.062	0.062	0.061	0.061	0.061	0.064	0.070
NMHC total	g HC	0.089	0.002	0.002	0.002	0.002	0.002	0.001	0.002
NMHC urban	g HC	0.089	0.002	0.002	0.002	0.002	0.002	0.001	0.002
NOx total	g NOx	1.000	0.129	0.129	0.195	0.195	0.195	0.052	0.347
NOx urban	g NOx	1.000	0.129	0.129	0.195	0.195	0.195	0.052	0.347
CO total	g CO	0.244	0.004	0.004	0.003	0.003	0.003	0.018	0.016
CO urban	g CO	0.244	0.004	0.004	0.003	0.003	0.003	0.018	0.016
PM10 total	mg PM10	37.38	6.93	6.93	6.84	6.84	6.84	3.81	1.54
PM10 urban	mg PM10	37.38	6.93	6.93	6.84	6.84	6.84	3.81	1.54
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0

Combustion	**Units**	**LS diesel (Aus)**	**LSdiesohol**	**Ethanol azeotropic (molasses-expanded sys.bound.)**	**Ethanol azeotropic (molasses-economic allocation)**	**Ethanol azeotropic (wheat starch waste)**	**Ethanol azeotropic (wheat)**	**Ethanol azeotropic (wheat) fired with wheat straw**	**Ethanol azeotropic (woodwaste)**	**Ethanol azeotropic (ethylene)**	**Hydrogen (from natural gas)**
Greenhouse	kg CO2	0.071	0.062	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.075
NMHC total	g HC	0.089	0.084	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.123
NMHC urban	g HC	0.089	0.084	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.123
NOx total	g NOx	1.000	0.914	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.096
NOx urban	g NOx	1.000	0.914	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.096
CO total	g CO	0.244	0.276	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.964
CO urban	g CO	0.244	0.276	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.964
PM10 total	mg PM10	37.38	28.41	28.03	28.03	28.03	28.03	28.03	28.03	28.03	35.04
PM10 urban	mg PM10	37.38	28.41	28.03	28.03	28.03	28.03	28.03	28.03	28.03	35.04
Energy Embodied	MJ LHV	0	0	0	0	0	0	0	0	0	0

Table A5.8

Summary of life cycle emissions from alternative fuels

		LS diesel (Aus)	ULS diesel (Aus)	ULS diesel (100% hydroprocessing)	Fischer-Tropsch diesel
Greenhouse	Precombustion	0.0203	0.0225	0.0206	0.0317
Greenhouse	Combustion	0.0707	0.0706	0.0706	0.0660
NMHC total	Precombustion	0.0599	0.0623	0.0606	0.0418
NMHC total	Combustion	0.0885	0.0718	0.0718	0.0507
NMHC urban	Precombustion	0.0287	0.0301	0.0291	0.0009
NMHC urban	Combustion	0.0885	0.0718	0.0718	0.0507
NOx total	Precombustion	0.1062	0.1220	0.1072	0.1436
NOx total	Combustion	1.000	0.852	0.852	0.870
NOx urban	Precombustion	0.046	0.060	0.047	0.005
NOx urban	Combustion	1.000	0.852	0.852	0.870
CO total	Precombustion	0.0239	0.0273	0.0242	0.0327
CO total	Combustion	0.2439	0.3079	0.3079	0.1968
CO urban	Precombustion	0.0130	0.0161	0.0132	0.0009
CO urban	Combustion	0.2439	0.3079	0.3079	0.1968
PM10 total	Precombustion	5.74	5.92	5.81	2.00
PM10 total	Combustion	37.38	27.94	27.94	24.18
PM10 urban	Precombustion	4.24	4.39	4.29	0.07
PM10 urban	Combustion	37.38	27.94	27.94	24.18
Energy Embodied	Precombustion	1.25	1.29	1.27	1.68

		LS diesel (Aus)	Biodiesel (canola)	Biodiesel (soybean)	Biodiesel (rape)	Biodiesel (tallow-expanded sys. boundary)	Biodiesel (tallow-eco.allocat.)	Biodiesel (waste oil)	Biodiesel (waste oil 10% original oil value)
Greenhouse	Precombustion	0.0203	0.0424	0.0320	0.0434	0.0411	0.0488	0.0069	0.0072
Greenhouse	Combustion	0.0707	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NMHC total	Precombustion	0.0599	0.1377	0.1643	0.1387	0.1348	0.0552	0.0549	0.0559
NMHC total	Combustion	0.0885	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038
NMHC urban	Precombustion	0.0287	0.1269	0.1554	0.1269	0.1239	0.0540	0.0539	0.0549
NMHC urban	Combustion	0.0885	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038
NOx total	Precombustion	0.1062	0.1367	0.1249	0.1544	0.1328	0.0274	0.0255	0.0304
NOx total	Combustion	1.000	1.132	1.132	1.132	1.132	1.132	1.132	1.132
NOx urban	Precombustion	0.046	0.061	0.077	0.063	0.060	0.027	0.025	0.030
NOx urban	Combustion	1.000	1.132	1.132	1.132	1.132	1.132	1.132	1.132
CO total	Precombustion	0.0239	0.0337	0.0814	0.0345	0.0328	0.0050	0.0046	0.0093
CO total	Combustion	0.2439	0.1334	0.1334	0.1334	0.1334	0.1334	0.1334	0.1334
CO urban	Precombustion	0.0130	0.0186	0.0720	0.0189	0.0181	0.0047	0.0044	0.0090
CO urban	Combustion	0.2439	0.1334	0.1334	0.1334	0.1334	0.1334	0.1334	0.1334
PM10 total	Precombustion	5.74	2.46	1.96	3.06	2.38	0.21	0.18	0.18
PM10 total	Combustion	37.38	26.80	26.80	26.80	26.80	26.80	26.80	26.80
PM10 urban	Precombustion	4.24	0.99	1.04	1.02	0.96	0.20	0.17	0.17
PM10 urban	Combustion	37.38	26.80	26.80	26.80	26.80	26.80	26.80	26.80
Energy Embodied	Precombustion	1.25	0.41	0.44	0.42	0.40	0.17	0.16	0.16

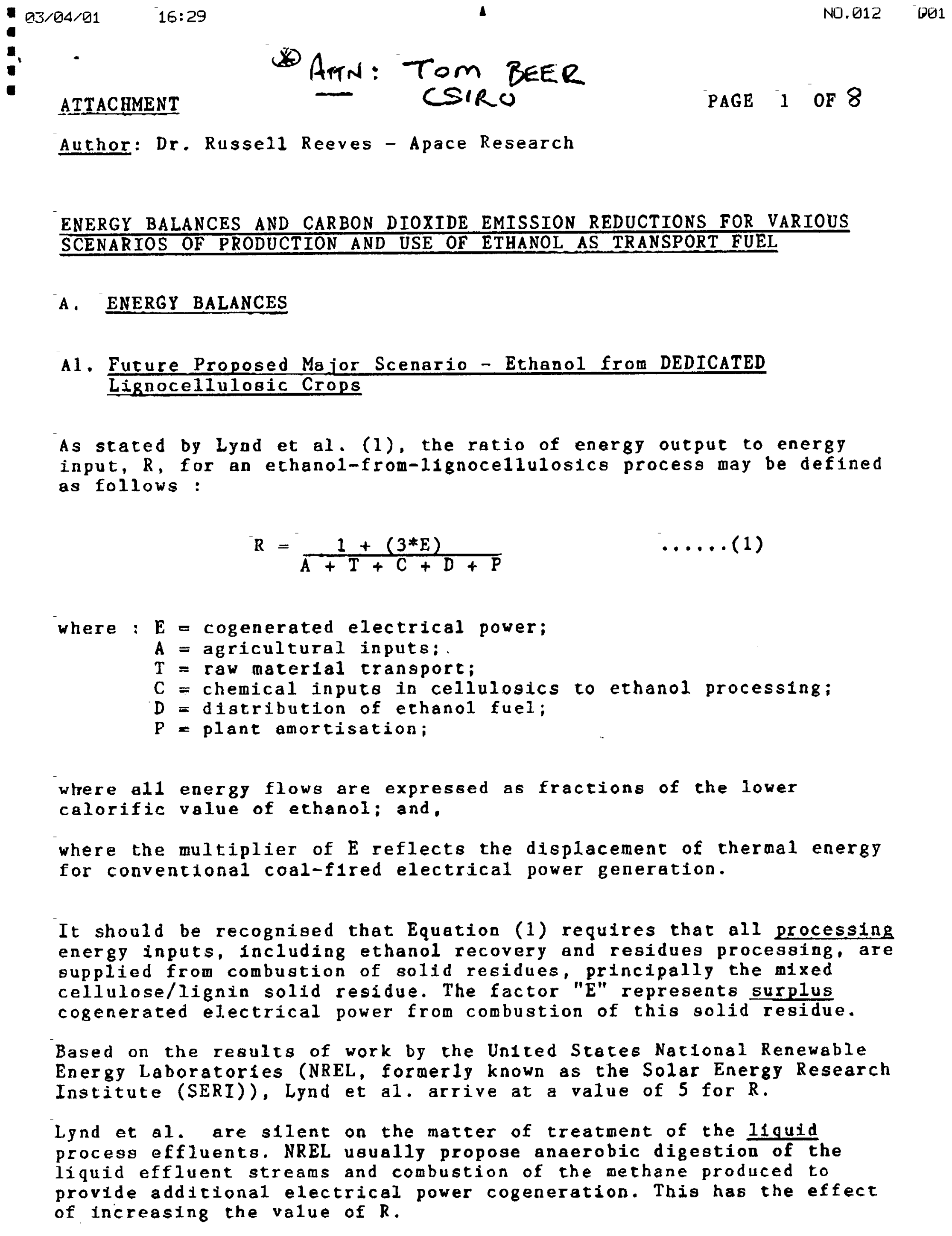
Table A5.8 (cont.)

Summary of life cycle emissions from alternative fuels

		LS diesel (Aus)	CNG (Electric compression)	CNG (NG compression)	LNG (from existing transmission line)	LNG (Shipped from north west shelf)	LNG (perth)	LPG (Autogas)	LPG (HD5)
Greenhouse	Precombustion	0.0203	0.0133	0.0153	0.0126	0.0133	0.0161	0.0183	0.0183
Greenhouse	Combustion	0.0707	0.0619	0.0619	0.0610	0.0610	0.0610	0.0639	0.0699
NMHC total	Precombustion	0.0599	0.0281	0.0309	0.0293	0.0293	0.0317	0.1082	0.1092
NMHC total	Combustion	0.0885	0.0022	0.0022	0.0018	0.0018	0.0018	0.0008	0.0023
NMHC urban	Precombustion	0.0287	0.0007	0.0011	0.0009	0.0001	0.0013	0.0798	0.0794
NMHC urban	Combustion	0.0885	0.0022	0.0022	0.0018	0.0018	0.0018	0.0008	0.0023
NOx total	Precombustion	0.1062	0.0296	0.0435	0.0328	0.0345	0.0745	0.0984	0.0972
NOx total	Combustion	1.000	0.129	0.129	0.195	0.195	0.195	0.052	0.347
NOx urban	Precombustion	0.046	0.014	0.027	0.017	0.000	0.003	0.043	0.040
NOx urban	Combustion	1.000	0.129	0.129	0.195	0.195	0.195	0.052	0.347
CO total	Precombustion	0.0239	0.0081	0.0122	0.0099	0.0103	0.0119	0.0224	0.0220
CO total	Combustion	0.2439	0.0038	0.0038	0.0034	0.0034	0.0034	0.0184	0.0163
CO urban	Precombustion	0.0130	0.0016	0.0051	0.0031	0.0001	0.0009	0.0124	0.0118
CO urban	Combustion	0.2439	0.0038	0.0038	0.0034	0.0034	0.0034	0.0184	0.0163
PM10 total	Precombustion	5.74	0.50	0.59	0.45	0.47	2.39	5.71	5.42
PM10 total	Combustion	37.38	6.93	6.93	6.84	6.84	6.84	3.81	1.54
PM10 urban	Precombustion	4.24	0.29	0.37	0.23	0.01	0.23	4.32	4.00
PM10 urban	Combustion	37.38	6.93	6.93	6.84	6.84	6.84	3.81	1.54
Energy Embodied	Precombustion	1.25	1.23	1.29	1.23	1.24	1.27	1.14	1.17

		LS diesel (Aus)	LSdiesohol	Ethanol azeotropic (molasses-expanded sys.bound.)	Ethanol azeotropic (molasses-economic allocation)	Ethanol azeotropic (wheat starch waste)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)	Hydrogen (from natural gas)
Greenhouse	Precombustion	0.0203	0.0227	0.0427	0.0741	0.0376	0.0680	0.0338	0.0081	0.1013	0.0882
Greenhouse	Combustion	0.0707	0.0621	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0432	0.0753
NMHC total	Precombustion	0.0599	0.0564	0.0131	0.0116	0.0039	0.0708	0.9138	0.5636	0.5843	0.0352
NMHC total	Combustion	0.0885	0.0843	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.1226
NMHC urban	Precombustion	0.0287	0.0279	0.0093	0.0100	0.0024	0.0096	0.8518	0.5626	0.5076	0.0012
NMHC urban	Combustion	0.0885	0.0843	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.0721	0.1226
NOx total	Precombustion	0.1062	0.1092	0.1308	0.1298	0.1023	0.3030	0.2489	0.0571	0.3384	0.0559
NOx total	Combustion	1.000	0.914	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.096
NOx urban	Precombustion	0.046	0.052	0.099	0.125	0.099	0.133	0.079	0.055	0.295	0.037
NOx urban	Combustion	1.000	0.914	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.096
CO total	Precombustion	0.0239	0.0792	0.5833	0.7456	0.0113	0.8026	3.4919	1.9377	0.0683	0.0129
CO total	Combustion	0.2439	0.2755	0.3089	0.3089	0.3089	0.3089	0.3089	0.3089	0.3089	0.9636
CO urban	Precombustion	0.0130	0.0689	0.5774	0.7436	0.0107	0.0146	2.7050	1.9377	0.0502	0.0048
CO urban	Combustion	0.2439	0.2755	0.3089	0.3089	0.3089	0.3089	0.3089	0.3089	0.3089	0.9636
PM10 total	Precombustion	5.74	5.26	0.93	0.30	21.54	25.08	45.25	26.95	5.23	0.72
PM10 total	Combustion	37.38	28.41	28.03	28.03	28.03	28.03	28.03	28.03	28.03	35.04
PM10 urban	Precombustion	4.24	3.85	0.32	0.19	21.44	22.23	42.39	26.85	4.65	0.46
PM10 urban	Combustion	37.38	28.41	28.03	28.03	28.03	28.03	28.03	28.03	28.03	35.04
Energy Embodied	Precombustion	1.25	1.17	0.43	0.50	0.45	0.70	0.81	2.77	3.56	1.50
Energy Embodied	Combustion	0	18	19	20	21	22	23	24	25	26

Appendix 6. Diesohol Information



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Attn: Tom Beer
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ATTACHMENT PAGE 1 OF 8

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ENERGY BALANCES AND CARBON DIOXIDE EMISSION REDUCTIONS FOR VARIOUS SCENARIOS OF PRODUCTION AND USE OF ETHANOL AS TRANSPORT FUEL

A. ENERGY BALANCES

A1. Future Proposed Major Scenario - Ethanol from DEDICATED Lignocellulosic Crops

As stated by Lynd et al. (1), the ratio of energy output to energy input, R, for an ethanol-from-lignocellulosics process may be defined as follows :

$$R = \frac{1 + (3*E)}{A + T + C + D + P} \qquad \ldots\ldots(1)$$

where : E = cogenerated electrical power;
A = agricultural inputs;
T = raw material transport;
C = chemical inputs in cellulosics to ethanol processing;
D = distribution of ethanol fuel;
P = plant amortisation;

where all energy flows are expressed as fractions of the lower calorific value of ethanol; and,

where the multiplier of E reflects the displacement of thermal energy for conventional coal-fired electrical power generation.

It should be recognised that Equation (1) requires that all processing energy inputs, including ethanol recovery and residues processing, are supplied from combustion of solid residues, principally the mixed cellulose/lignin solid residue. The factor "E" represents surplus cogenerated electrical power from combustion of this solid residue.

Based on the results of work by the United States National Renewable Energy Laboratories (NREL, formerly known as the Solar Energy Research Institute (SERI)), Lynd et al. arrive at a value of 5 for R.

Lynd et al. are silent on the matter of treatment of the liquid process effluents. NREL usually propose anaerobic digestion of the liquid effluent streams and combustion of the methane produced to provide additional electrical power cogeneration. This has the effect of increasing the value of R.

Lynd et al. and NREL are unaware of the Apace technology for the production of ethanol from lignocellulosics.

If the Apace technology, in particular the Apace simultaneous ethanol recovery/waste treatment process, proves successful the effect will be a significant increase in the value of R from the current value of 5 to a value of at least 7.

The above mentioned increase is achieved because the Apace technology significantly reduces the processing energy input. This in turn leaves an increased amount of cellulose/lignin solid residue available for electrical power cogeneration.

Immediate Future-Proposed Major Scenario - Ethanol from Lignocellulosic RESIDUE Materials

In this scenario the agricultural energy input (A) in Equation 1 can be considered as zero. Using the remaining energy input values ascribed by Lynd et al., R then has a value in excess of 12.

With use of the Apace technology R would have a value in excess of 17

Present Situation - Production of Ethanol by the Manildra Group from WASTE Starch Associated with Production of Wheat Products

In the Manildra case the processing energy input, principally that of distillation for ethanol recovery, is currently being switched from combustion of black coal to combustion of natural gas.

Unlike the case with the ethanol-from-lignocellulosics process, there are no solid residues available for combustion from Manildra's ethanol-from-starch plant.

All liquid effluent streams, principally the underflow from the "stripping" distillation column, are currently irrigated onto surrounding land used for intensive pasture production.

The liquid effluent has displaced use of conventional fertilisers and significantly increased the soil carbon content.

the present Manildra operation Equation (1 then becomes

$$R = \frac{1}{A + T + S + C + D + P} \qquad ......(1b)$$

where : S = processing energy input; and,

where all other factors are as defined in Equation 1).

The Manildra plant is a modern, integrated ethanol-from-starch plant based on well-proven conventional technology. Such plants have a processing energy input of approximately 4.5 MJ/litre of azeotropic ethanol and 5.9 MJ/litre of anhydrous ethanol (ref.2). Based on a lower calorific value of 19.43 MJ/litre for azeotropic ethanol and 21.15 MJ/litre for anhydrous ethanol, and assuming natural gas to steam conversion efficiency of 70%, this converts to a value of 0.33 for factor "S" in Equation (1b) for azeotropic ethanol, and 0.40 for anhydrous ethanol. Manildra have an on-going research and development programme on all stages of the starch-to-ethanol conversion process, and will be supporting work by Apace Research on a low energy requirement simultaneous ethanol recovery/liquid effluent treatment process. Improvements in any stage of the overall starch-to-ethanol conversion process, most particularly in the ethanol recovery and effluent treatment stages, serve to increase the energy balance and reduce greenhouse gas emissions.

A significant proportion of the starch feedstock used by Manildra for ethanol production is waste starch from Manildra's gluten production, or is derived from reject grain. For these starch feedstocks the agricultural energy input, factor "A" in Equation (1b), is zero. Factor "A" will need to be calculated for that proportion of the starch feedstock which is derived from prime wheat. Based on detailed analyses by the United States Department of Agriculture and Department of Energy on the energy input for corn production in the United States (ref. 3), factor "A" for wheat production in Australia is likely to be approximately 0.22. Manildra have a policy of applying best farming practice to wheat production. This will serve to steadily increase the energy balance and reduce greenhouse gas emissions.

If 50% of the starch feedstock used for ethanol production was derived from prime wheat, factor "A" in Equation (1b) would thus have a value of approximately 0.11.

Because the ethanol distillery is annexed to the existing starch/gluten plant the raw material transport input, factor "T", for the waste starch stream is zero. Factor "T" will need to be calculated for that proportion of the starch feedstock which is derived from prime and reject wheat. Transport of Manildra's wheat and starch is predominantly by rail, resulting in a higher energy balance and lower greenhouse emissions compared with road transport. If 55% of the starch feedstock used for ethanol production was from prime and reject wheat, factor "T" in Equation (1b) would have a value of approximately 0.02.

Chemical inputs and ethanol fuel distribution, factors "C" and "D" respectively, in ethanol-from-starch production are approximately the same as for ethanol-from-lignocellulosics production and can be taken as 0.01 (ref.1).

Due to the ethanol distillery being annexed to the existing starch/gluten plant and utilising already existing pretreatment and steam generation plant, the plant amortisation factor "P" for the Manildra distillery is considerably less than that of a new, stand-alone plant. In addition, because there is no solid residue with the Manildra ethanol-from-starch plant there is no solids handling or electrical power cogeneration equipment typical of an ethanol-from-lignocellulosics plant. Accordingly, a value of 0.01 is assumed for factor "P" (ref.1).

Thus from Equation (1b), R will initially have a value of approximately 2.0 for azeotropic ethanol and approximately 1.8 for anhydrous ethanol.

This compares favourably with existing best practice ethanol-from-corn plants in the United States which have a value for R of 1.87 for anhydrous ethanol. New, leading-edge United States ethanol-from-corn plants have a value for R of 2.21 for anhydrous ethanol (ref.3).

It is interesting to compare the value of R for Manildra's ethanol with that of CSR's azeotropic ethanol produced from molasses at Sarina in Queensland.

Molasses is the residue from the production of crystal sugar for food.

However, in the case of CSR's azeotropic ethanol-from-molasses plant, the processing energy input is supplied from combustion of the sugar cane bagasse.

Surplus bagasse is also used by CSR for electrical power cogeneration.

Equation (1) is thus relevant to this case

Agricultural input (A) can be considered as zero and raw material transport (T) is insignificant.

Chemical inputs into the ethanol-from-molasses process are likewise insignificant, being considerably less than for the ethanol-from-lignocellulosics and ethanol-from-starch processes.

Thus, even if no electrical power cogeneration is assumed (i.e., E = 0), and using the values for factors "D" and "P" ascribed by Lynd et al., R has a value of approximately 20 for CSR's azeotropic ethanol.

B. CARBON DIOXIDE BALANCES

As stated by Lynd et al., an indication of the contribution of the various ethanol fuel production scenarios to carbon dioxide accumulation in the atmosphere is the net carbon dioxide produced per unit energy N. This parameter may be estimated from :

$$N = \frac{f}{R} * C \qquad \ldots(2)$$

where f = the fraction of energy inputs met by fossil fuels;
C = carbon dioxide produced per unit energy for fossil energy inputs; and,
R is as defined in Equation (1).

All the energy inputs identified in Equation (1) and (1b) can be satisfied either by fossil fuels (corresponding to f = 1) or by fuels that do not contribute to carbon dioxide accumulation in the atmosphere, such as wood, bagasse or lignin in stationary applications such as boilers and neat ethanol produced efficiently from lignocellulosics for mobile applications (corresponding to f = 0).

The best case scenario is when f = 0, which results in 100% reduction in carbon dioxide emission.

B1. Ethanol from DEDICATED Lignocellulosic Crops

Reference to section A1 and Equation (2) above shows that R = 5 and f = 1 corresponds to a worst case scenario of approximately an 80% reduction in carbon dioxide emission associated with the use of neat ethanol as fuel compared to the use of fossil fuels, assuming equivalent thermal efficiency of use.

With use of the Apace technology and R = 7, the worst case scenario results in approximately an 85% reduction in carbon dioxide emission

The best case scenario is when f = 0, which results in a 100% reduction in carbon dioxide emission.

B2. Ethanol from Lignocellulosic RESIDUE Materials

Reference to section A2 and Equation (2) above shows that R = 12 and f = 1 corresponds to a worst case scenario of approximately a 92% reduction in carbon dioxide emission associated with the use of neat ethanol as fuel compared to the use of fossil fuels.

With use of the Apace technology and R = 17, the worst case scenario results in approximately a 94% reduction in carbon dioxide emission.

Again the best case scenario is when f = 0 which results in a 100% reduction in carbon dioxide emission.

B3. Production of Ethanol by the Manildra Group from WASTE Starch Derived from Gluten/Starch Plant

In the Manildra ethanol-from-starch plant natural gas is currently replacing black coal for the processing energy input. Chemical input is produced using fossil fuels. Diesohol E15 is replacing diesel as the transport fuel used for ethanol distribution. However, because the energy inputs are dominated by the processing energy input, a value of 1 is assigned to the factor "f" as a worst case scenario. Factor "C " for natural gas is approximately 56mg/KJ (ref.4).

Thus, for Manildra anhydrous ethanol N = 31 mgCO2/KJ, and for Manildra azeotropic ethanol N = 28 mgCO2/KJ. This compares to approximately 80 mgCO2/KJ for petrol and diesel (refs.1,4,5).

This corresponds to a 61% reduction in net carbon dioxide emission associated with the use of neat Manildra anhydrous ethanol and a 65% reduction with use of neat Manildra azeotropic ethanol compared to the use of petrol or diesel, assuming equivalent thermal efficiency of use. However the thermal efficiency of internal combustion engines increases when operating on neat ethanol and on ethanol blends compared to both neat petrol and diesel fuel, resulting in slightly greater reductions in net carbon dioxide emission.

It is noted that Manildra will be introducing improved ethanol production methods and replacing fossil fuel inputs with renewable fuel inputs as these become available. The latter measure in particular will dramatically increase the effectiveness of Manildra ethanol in reducing net carbon dioxide emission compared with use of diesel fuel and petrol.

Use of neat CSR azeotropic ethanol for which R = 20 would, under a worst case scenario of f = 1, result in an approximately 95% reduction in carbon dioxide emission compared to the use of petrol or diesel.

Ethanol Blend Fuel Example: DIESOHOL E15

One litre of Diesohol E 15 is comprised of:

0.845 litres of diesel fuel
0.150 litres of azeotropic ethanol
0.005 litres of chemical emulsifier

The emulsifier is a petrochemical comprised of only the elements carbon, hydrogen and oxygen. Due to its chemical nature and low concentration in Diesohol the emulsifier is assumed to be diesel fuel

Typical lower calorific values for the relevant fuels are:

36.0 MJ/litre for diesel fuel
19.4 MJ/litre for azeotropic ethanol

From Section B above, typical values for net carbon dioxide emission, N, are as set out below. The values for azeotropic ethanol are worst case scenarios based on factor f = 1 and no use of the Apace technology.

80 mgCO2/KJ for diesel fuel
28 mgCO2/KJ for Manildra azeotropic ethanol
16 mgCO2/KJ for ethanol from dedicated lignocellulosic crops
6 mgCO2/KJ for ethanol from lignocellulosic residue materials
4 mgCO2/KJ for CSR azeotropic ethanol from molasses

Thus the net carbon dioxide emission from one litre of neat diesel fuel is approximately 2.88 Kg, compared to 2.53 Kg from one litre of Diesohol E15 made with Manildra azeotropic ethanol. As noted in Section A3 above however, the liquid effluent from Manildra's ethanol production is used to displace conventional fertilisers and to increase soil carbon content. The reduction in carbon dioxide emission per litre of ethanol production associated with these aspects has been estimated by NSW Department Of Agriculture to be approximately 0.18 Kg thus reducing the net carbon dioxide emission from one litre of Diesohol E15 to 2.50 Kg. This corresponds to a 13.2% reduction in net carbon dioxide emission compared to the use of neat diesel fuel.

The reduction in net carbon dioxide emission is 13.2%, 14.2% and 14.6% for Diesohol E15 made with ethanol from dedicated lignocellulosic crops, lignocellulosic residue materials and CSR molasses, respectively

"Real world" field trials of Diesohol E15 in various countries have shown no significant increase in volumetric fuel consumption of vehicles using Diesohol E15 compared to neat diesel fuel. This is due to the increased thermal efficiency of diesel engines when operating on emulsion fuels containing alcohols and/or water. However, if a 5% increase in volumetric fuel consumption is assumed as a worst case scenario then the use of Diesohol E15 produced from Manildra azeotropic ethanol will result in an approximately 9% reduction in net carbon dioxide emission compared to the use of neat diesel fuel. In the case of CSR azeotropic ethanol the reduction is approximately 10.4%

It should be recognised that Diesohol E15 represents a conservative level of ethanol substitution and that higher levels of ethanol substitution are possible. Up to 30% of ethanol by volume (Diesohol E30) can be used in existing diesel engines with minor adaptation.

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References

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4. Milton, B.E., Proceedings NGV-88 Conference, Sydney, October 1988 Volume 2, Paper 22, p. 4
5. NRMA - Rules for "1993 Energy Challenge" Event

Appendix 7 Euro Standards

The terms of reference, given in Appendix 1, requested a determination of:

> an average "grams of emission per megajoule" for both greenhouse emissions and air quality emissions for both light and heavy vehicle Euro Standards I to IV. (The light vehicle Euro Standards are measured in grams per kilometer and each of the light vehicle Euro standards has three vehicle categories.)

We have obtained the Euro standards from Greening (2000, 2001) and from Arcoumanis (2000). Each section of the appendix provides the relevant Euro standard, as promulgated, and then converts the standard to a representative emission per megajoule of fuel consumed.

A7.1 Heavy duty vehicles

The EU standards for heavy duty vehicles (both gas and diesel) are given in Table A7.1.

Table A7.1
EU standards for heavy duty vehicles (g/kWh)

	CO	NOx	PM	THC	NMVOC	CH_4 NGV only	Test cycle
Euro1	4.5	8*	0.36*	1.1			ECE R-49
Euro2	4	7	0.15*	1.1			ECE R-49
Euro3	2.1	5	0.1	0.66			ESC/ELR
Euro3	5.45	5	0.16		0.78	1.6	ETC
Euro4-Level1	1.5	3.5	0.02	0.46			ESC/ELR
Euro4-Level1	4	3.5	0.03		0.55	1.1	ETC
Euro4-Level2	1.5	2	0.02	0.25			ESC/ELR
Euro4-Level2	3	2	0.02		0.4	0.65	ETC

* lowest value is given.

The heavy-duty vehicle standards are converted to g/MJ fuel consumed in Table A7.2 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 33%. This value may be compared to the truck and bus data found in Chapter 2 of Part 3 where the fuel to wheel efficiency of the bus ranged from 24 to 35% and for the truck ranged from 32 to 38% over the extreme range of driving conditions, congested-urban to highway cycles respectively, as identified (by means of the average speed) in the base of the CO_2 and NOx graphs.

Table A7.2
EU standards for heavy duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC	NMVOC	CH_4 NGV only	Test cycle
Euro1	3.75	6.67	0.30	0.92			ECE R-49
Euro2	3.33	5.83	0.13	0.92			ECE R-49
Euro3	1.75	4.17	0.08	0.55			ESC/ELR
Euro3	4.54	4.17	0.13		0.65	1.33	ETC
Euro4-Level1	1.25	2.92	0.02	0.38			ESC/ELR
Euro4-Level1	3.33	2.92	0.03		0.46	0.92	ETC
Euro4-Level2	1.25	1.67	0.02	0.21			ESC/ELR
Euro4-Level2	2.50	1.67	0.02		0.33	0.54	ETC

A7.2 Diesel light commercial vehicles with weight below 1305 kg

The EU standards for diesel passenger cars and diesel light commercial vehicles below 1305 kg mass are given in Table A7.3

Table A7.3
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2	1		0.08	0.7
Euro3	0.64	0.5	0.05	0.56
Euro4	0.5	0.25	0.025	0.3

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.4 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 10.5 MJ/km.

Table A7.4
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2	0.10		0.01	0.07
Euro3	0.061	0.048	0.005	0.053
Euro4	0.048	0.024	0.002	0.029

A7.3 Diesel light commercial vehicles with weight between 1305 kg and 1760 kg

The EU standards for diesel passenger cars and diesel light commercial vehicles between 1305 kg and 1760 kg mass are given in Table A7.5

Table A7.5
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	0.8	0.65	0.07	0.72
Euro4	0.63	0.33	0.04	0.39

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.6 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 10.5 MJ/km.

Table A7.6
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	0.076	0.062	0.007	0.069
Euro4	0.060	0.031	0.004	0.037

A7.4 Diesel light commercial vehicles with weight greater than 1760 kg

The EU standards for diesel passenger cars and diesel light commercial vehicles above 1760 kg kg mass are given in Table A7.7

Table A7.7
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	0.95	0.78	0.1	0.86
Euro4	0.74	0.39	0.06	0.46

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.8 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 10.5 MJ/km.

Table A7.8
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	0.090	0.074	0.010	0.082
Euro4	0.070	0.037	0.006	0.044

A7.5 Petrol light commercial vehicles with weight below 1305 kg

The EU standards for petrol passenger cars and petrol light commercial vehicles below 1305 kg mass are given in Table A7.9.

Table A7.9
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2	2.2	0.252		0.341
Euro3	2.3	0.15		0.2
Euro4	1	0.08		0.1

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.10 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 2.4 MJ/km.

Table A7.10
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2	0.92			0.14
Euro3	0.96	0.06		0.08
Euro4	0.42	0.03		0.04

A7.6 Petrol light commercial vehicles with weight between 1305 kg and 1760 kg

The EU standards for petrol passenger cars and petrol light commercial vehicles between 1305 kg and 1760 kg mass are given in Table A7.11

Table A7.11
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	4.17	0.18		0.25
Euro4	1.81	0.1		0.13

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.12 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 2.4 MJ/km.

Table A7.12
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	1.74	0.08		0.10
Euro4	0.75	0.04		0.05

A7.7 Petrol light commercial vehicles with weight greater than 1760 kg

The EU standards for petrol passenger cars and petrol light commercial vehicles above 1760 kg kg mass are given in Table A7.13

Table A7.13
EU standards for light duty vehicles (g/km)

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	5.22	0.21		0.29
Euro4	2.27	0.11		0.16

The light duty vehicle standards are converted to g/MJ fuel consumed in Table A7.14 for a vehicle in which the efficiency of conversion of fuel energy to wheel energy is 2.4 MJ/km.

Table A7.14
EU standards for light duty vehicles converted to g/MJ fuel

	CO	NOx	PM	THC+NOx
Euro1				
Euro2				
Euro3	2.18	0.09		0.12
Euro4	0.95	0.05		0.07

Appendix 8 Carbon Dioxide Emissions Factors

A8.1 Introduction

Table A.2 of Workbook 3.1 of the Australian National Greenhouse Gas Inventory (1996) specifies emission factors for carbon dioxide emissions in g/MJ. This appendix provides the emission factors for all the fuels used in this study.

Fuel	Carbon dioxide emission factor (g/MJ)	Notes
Low Sulfur Diesel	69.7	Workbook 3.1 – NGGIC (1996)
Ultra-low Sulfur Diesel	69.7	All diesel fuel taken to have the same emission factor
Fischer-Tropsch Diesel	69.7	All diesel fuel taken to have the same emission factor
Biodiesel	89	Beer et al. (2000) - Appendix 4
Canola	89	Assumed to be the same as biodiesel
Hydrated Ethanol	62.5	Stoichiometry (see note 1, 2)
Diesohol	69.7	Table 7.4 and Table 7.5 of Part 2 indicate that diesel and diesohol emissions of CO_2 do not differ.
CNG	54.4	Workbook 3.1 – NGGIC (1996) for natural gas
LNG	54.4	Workbook 3.1 – NGGIC (1996) for natural gas
LPG-HD5 (Propane)	59.8	Stoichiometry (see note 3)
Butane	61.3	Stoichiometry (see note 4)
LPG (Autogas)	59.4	Workbook 3.1 – NGGIC (1996) for liquefied petroleum gas
PULP	66	Workbook 3.1 – NGGIC (1996) for automotive gasoline
Anhydrous ethanol	62.5	Stoichiometry (see note 1, 2)
Petrohol	67.8	Based on reformulated gasoline results in MacLean (1998)
Hydrogen	0	No tailpipe emissions of CO_2

1. The calculations in the Workbook of the National Greenhouse Gas Inventory Committee (1996) are based on the gross calorific value (higher heating value). We have thus used the gross calorific value for the stoichiometric calculations. However, the note accompanying the table of fuel properties found on the alternative fuels data center web site (www.afdc.doe.gov) states: “since no vehicles in use, or currently being developed for future use, have powerplants capable of condensing the moisture of combustion, the lower heating value should be used for practical comparisons between fuels.”
2. Based on the stoichiometry of ethyl alcohol with a gross calorific value of 30.6 MJ/kg.
3. Based on the stoichiometry of propane with a gross calorific value of 50.2 MJ/kg.
4. Based on the stoichiometry of butane with a gross calorific value of 49.5 MJ/kg.

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Appendix 9 Nitrogen Emissions from Vehicles

The aim of this appendix is to review the mechanisms that are believed to be responsible for the emissions of oxides of nitrogen (NOx) and nitrous oxide (N_2O) from motor vehicles so as to demonstrate that they are independent. One depends primarily on the air/fuel mixture, the other depends on the nature of the catalyst (if any) on the vehicle. It is not possible to estimate N_2O emissions on the basis of known NOx emissions.

A9.1 NOx Emissions

The presence of CO, NO and SO are evidence of incomplete combustion. The carbon, nitrogen and sulfur (if any) in the fuel combine with atmospheric oxygen. Complete combustion produces CO_2, NO_2, and SO_2. Automobile exhaust consists of a mixture of all these six gases. In particular, the amount of NO emitted from the exhaust depends on the peak temperature reached within the combustion system, and on the air/fuel ratio, as depicted in Figure 10.1 of Part 2. Once NO has been released into the atmosphere, it reacts with oxygen and ultraviolet light, and is slowly converted to NO_2 and ozone.

A9.2 N_2O Emissions

Workbook 3.1 of the Australian National Greenhouse Gas Inventory (1996: p.32) notes that there is considerable evidence to suggest that the use of catalysts to control pollutants actually increases the amount of N_2O emitted. There is also evidence that the amount of N_2O that is emitted increases as the catalyst ages.

A9.3 Conclusion

One may expect a vehicle without a catalyst to emit *higher* values of NOx than a vehicle equipped with a catalyst. However, one expects a vehicle without a catalyst to emit *lower* values of N_2O than a vehicle that is equipped with a catalyst. Thus, although there is probably an inverse relationship between NOx emissions and N_2O emissions, the complexity of the interaction between combustion temperature, air/fuel ratio, and the properties of the catalyst are such that it is not possible, at this stage, reasonably to approximate N_2O emissions from NOx levels.