Hybrid Electric Vehicle

GREENHOUSE GAS
AND LIFE CYCLE ISSUES

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31 July 2000

Contribution to the Chief Executive's Special Project on Low Emission Vehicles

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Toyota Prius Hybrid Electric Car

aXcessaustralia Concept Car Mk 1

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Executive Summary

This report presents data on the greenhouse-gas emissions from motor vehicles under two assumptions – the first is a business-as-usual scenario in which Australian motor vehicle use continues to be dominated by the present generation of engines. The second assumption is a scenario in which there is a gradual uptake of hybrid electric vehicles (HEV) and low emission vehicles (LEV). The main conclusions to emerge from this analysis are that:

1. A typical HEV emits 2.0 tonnes CO_2-equivalents per annum on a life cycle basis, if the batteries are charged during the normal driving of the vehicle. This is a 66% reduction in greenhouse gases compared to the average Australian passenger car.

2. The dominant greenhouse-gas emissions from motor vehicles manifest themselves in the CO_2 emitted during the combustion of the motor fuel.

3. The other greenhouse gases, CH_4 and N_2O, contribute about 10% of the greenhouse-gas emissions from a motor vehicle, when expressed in CO_2-equivalents based on 100-year global warming potentials.

4. Life-cycle analyses of hybrid vehicles indicate that fuel combustion comprises about 80% of the total energy consumption.

5. There are significant greenhouse-gas emissions associated with battery charging in all Australian States except for Tasmania. Even 4 kW-hour every two weeks can increase greenhouse-gas emissions associated with the vehicle by up to 8%.

6. In all Australian States, except for Tasmania, recharging the battery using electricity emits more greenhouse gases than recharging the vehicle by driving it and consuming petrol. In Victoria recharging the battery using domestic electricity emits twice the greenhouse gases of petrol-based battery charging, but even at the domestic electricity tariff costs only half that of using petrol to recharge the battery.

7. The use of the HEV/LEV will reduce greenhouse-gas emissions from passenger vehicles. If 90% of the vehicle fleet consists of HEV/LEV vehicles then we estimate greenhouse-gas emissions from petrol-driven passenger cars to reduce by 61%.

1 Objectives of this study

This study responds to a request to examine the greenhouse-gas emissions, on a life-cycle basis, from Australian hybrid electric vehicles. There are two aspects to this request. The first aspect relates to the life-cycle emissions of greenhouse gases from a single vehicle. The second aspect relates to the reduction in overall greenhouse-gas emissions from the total Australian vehicle fleet if there is substantial market penetration of hybrid electric vehicles.

2 Present Australian Inventory Guidelines on Transport Emissions

This report presents data on the greenhouse-gas emissions from motor vehicles under two assumptions – the first is a business-as-usual scenario in which Australian motor vehicle use continues to be dominated by the present generation of engines. The second assumption is a scenario in which there is a gradual uptake of hybrid electric vehicles (HEV) and low emission vehicles (LEV).

Methodologies for greenhouse-gas inventories are now firmly established at international and national levels. The benefit of this approach is that it provides a basis for comparisons between different time periods, avoids double counting or omission of emissions and standardises the statistics to be collected for future inventories. In this report the methodology given in National Greenhouse Gas Inventory Committee (1996b) has been followed as closely as possible.

The National Greenhouse Gas Inventory Committee (1996b) methodology for calculating greenhouse-gas emissions other than carbon dioxide (CO_2) applies a set of “known” emission factors to the vehicle kilometres travelled (VKT) by each class and fuel type of vehicle. CO_2 emissions are calculated from fuel volumes using known factors dependent upon the energy content and density of the fuel. These calculations are complementary if independent data on either fuel consumption rates (in L/100 km) or fuel efficiency (in km/L) are available. The reliability of estimates of emissions is dependent upon, in the first instance, the reliability of the VKT and fuel volume data. The reliability of VKT data is very much dependent upon the statistical sampling strategy used for its collection. Fuel volume data, on the other hand, while seemingly easier to gather statistics on, has a degree of uncertainty associated with it. The uncertainty arises because allowances have to be made for use by other activities besides the on-road motor vehicle fleet. Emission rates from motor vehicles vary greatly depending upon the vehicle type, fuel used, mode of driving, maintenance history, emission controls fitted and age of vehicle.

The greenhouse gases considered in this report are carbon dioxide, methane, and nitrous oxide. The other greenhouse gases, namely nitrogen oxides, carbon monoxide, non-methane volatile organic compounds and sulphur oxides will not be considered for two reasons. Firstly, they are being examined in detail as part of the air pollution considerations of the HEV/LEV. Secondly, these gases are secondary greenhouse gases that are not assigned global warming potentials in their own right, so that there is no agreed uniform method of quantifying these different gases in relation to greenhouse-gas issues. In addition, chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) emissions from air conditioners in vehicles are not considered here because they are regulated under the Montreal protocol on substances that deplete the ozone layer.

2.1 Emissions

Carbon dioxide emissions are the natural consequence of the combustion of any fuel; the amount produced can only be reduced by reducing energy consumption or improvements in fuel consumption efficiencies. The other gases are by-products of the combustion. Their emissions can be reduced by improvements to emission control systems and/or engine design. In the case of non-methane volatile organic compounds there is an additional source due to unburnt fuel and evaporative losses. Currently, non-methane hydrocarbons, nitrogen oxides and carbon monoxide emissions from cars are regulated according to Australian Design Rule ADR 37/00. There are presently plans to introduce stricter emission controls, firstly by introducing ADR 79/00 requiring vehicles to meet Euro2 emission standards by 2003, and then by introducing ADR 79/01 requiring vehicles to meet Euro3 standards by 2007.

2.2 Comparisons with Previous Work

Table 1 lists the emissions of greenhouse gases from petrol-driven passenger cars, and all the sectors and sub-sectors that include these cars, according to the 1995 Greenhouse Gas Inventory (National Greenhouse Gas Inventory Committee, 1997). Transport emits about 24% of the national CO_2 emissions of 268,000 Gg, but only about 17% of total greenhouse-gas emissions of 402,000 Gg CO_2-equivalents.

Table 1
Australian greenhouse-gas emissions from the transport sector and its sub-sectors in 1995

	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	CO_2-equiv. (Gg)
Transport	65185	25.6	9.8	68758
Road Transport	56907	20.5	9.6	60306
All Passenger Cars	37098	16.6	9.0	40237
Petrol Passenger Cars	33180	15.7	8.93	36278

Source: National Greenhouse Gas Inventory Committee, 1997

The Australian methodology for the calculation of greenhouse-gas emissions from passenger cars (National Greenhouse Gas Inventory Committee, 1997) subdivides petrol passenger cars into three classes – post 1985, 1976-1985, pre-1976. These classes were chosen because vehicle emission controls were first introduced in 1976, and unleaded petrol became mandatory for all new cars after 1985. Table 2 shows the estimates of the energy use, greenhouse-gas emissions, and air pollution loads for these vehicle classes during 1995.

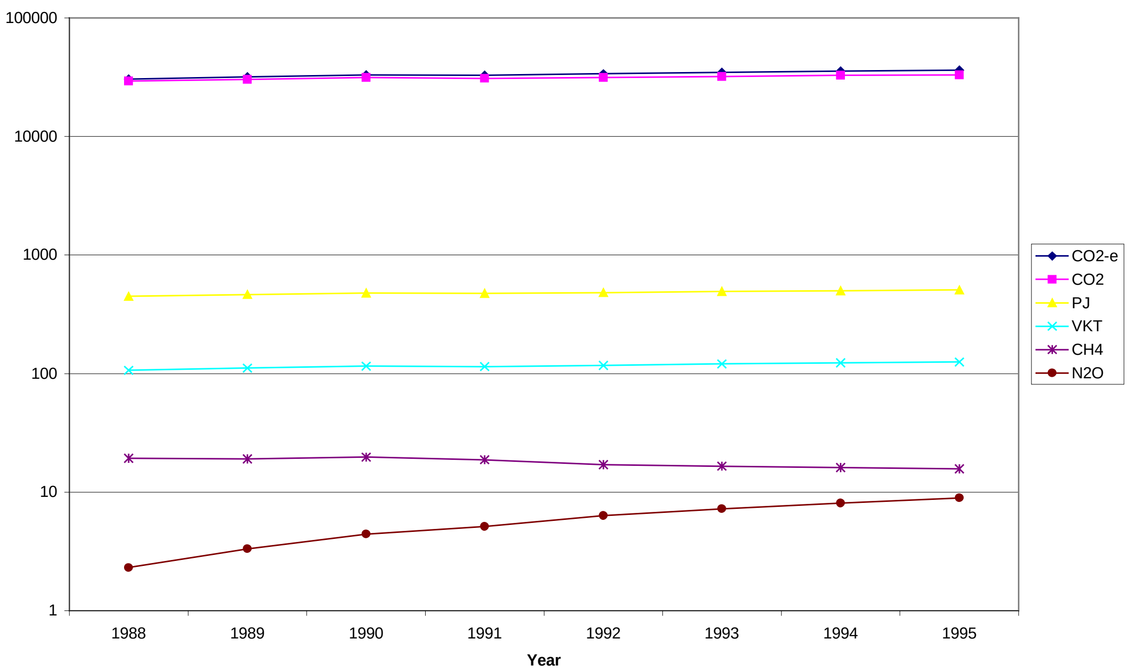
Figure 1 plots the annual variation from 1988 to 1995 (inclusive) of the vehicle kilometres travelled (VKT, in billions of km), the energy usage (PJ), and the emissions of CO_2, CH_4 and N_2O, and the CO_2-equivalents, all in Gg.

Table 2
Australian energy use, greenhouse-gas emissions and air pollution loads for 1995 for major petrol driven passenger car classes.

	Energy use (PJ)	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	NOx (Gg)	CO (Gg)	NM-VOC (Gg)	SOx (Gg)
Post 1985	321.5	21010	8.82	8.76	83.4	760.3	165	4.86
1976-1985	162.9	10642	5.54	0.14	81.8	1126.2	157.7	2.46
Pre 1976	23.4	1528	1.34	0.02	13.2	257.9	36.2	0.35
Total	507.8	33180	15.7	8.93	178.5	2144.3	358.9	7.67

Source: National Greenhouse Gas Inventory Committee, 1997

Figure 1
Time series of energy use (in PJ), VKT (in Tm) and greenhouse-gas emissions (in Gg) of Australian petrol driven passenger cars.



It is noticeable in Figure 1 that, despite the upward creep in VKT (from 106.7 billion km in 1988 to 125.2 billion km in 1995), there has been only a slight increase in energy usage from 449.5 PJ to 507.8 PJ. Methane emissions have declined during this period but nitrous oxide (N_2O) emissions have increased as a result of the use of three-way catalytic converters. Beer (1995) has shown that stringent emission controls are successful in decreasing atmospheric loads in the short term, as old vehicles are replaced by newer vehicles with lower emissions. In the longer term all of the vehicle fleet consists of lower emission vehicles and then the increase in passenger car numbers and in VKT leads to an increase in atmospheric loads.

3 The Automobile Life Cycle

Much of the material in this Section is taken from Kuhndt & Bilitewski (1999), supplemented by material found on the Toyota Web site.

Today vehicles consist of approximately 15,000 parts. Steel, iron, plastic and non ferrous metal dominate automobile construction. They account for more than 80% of material used for current vehicles. A common trend in the material composition of a car is toward increasing use of lightweight materials, especially towards the use of numerous types of plastics and non ferrous metals such as aluminium, copper and magnesium. Table 3, taken from Kuhndt & Bilitewski (1999), shows the material composition of current vehicles.

Table 3
Passenger Car's Material Ratio

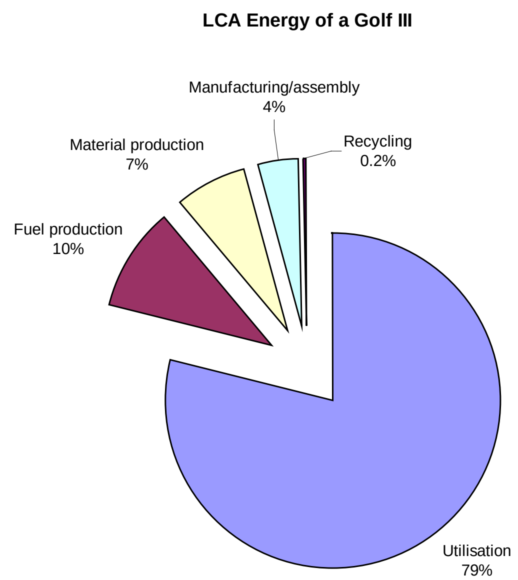
Material	Material Ratio (% by weight)			
	Generic US vehicle[1]	Generic Japanese vehicle[2]	Generic EU compact vehicle[3]	Golf III[3]
Steel and iron	67	72.2	65	64
Plastic	8	10.1	12	16
Glass	2.8	2.8	2.5	3.1
Rubber	4.2	3.1	6	4
Fluids and Lubricants	6	3.4	2.5	5
Non ferrous metal	8	6.2	8	1.6
Electric cable				1.3
Insulation				1.1
Paint				0.9
Other materials	4	2.2	4	3
Total weight (kg)	1438	1270	1210	1025

Source: 1 Keoleian et al. (1997): 2 Kobayashi (1996): 3 Schweimer & Schuckert, M. (1996)

The generic European vehicle shows a downward trend in metal content, which now accounts for about 65% of the total weight. The plastic content of current models has increased fourfold over the last twenty years and it is expected that this will continue to increase before leveling off at about 15% by the year 2000 (Peters, 1996). The Golf III has already achieved this level of plastic content.

The *utilization* of an automobile consumes about 80% of the total primary energy consumption of the life cycle of an automobile. This refers to the energy involved in production, utilisation and disposal of the vehicle itself. The LCA of the Golf III confirms that the "use phase" is the dominant phase (Figure 2).

Figure 2
The in-process and direct greenhouse-gas emissions (0.0356 Gg CO_2) during the life cycle of a Golf III for a life of 150,000 km, primary energy consumption of 540 GJ and a fuel consumption of 12.3 km/L (Kuhndt and Bilitewski, 1999)



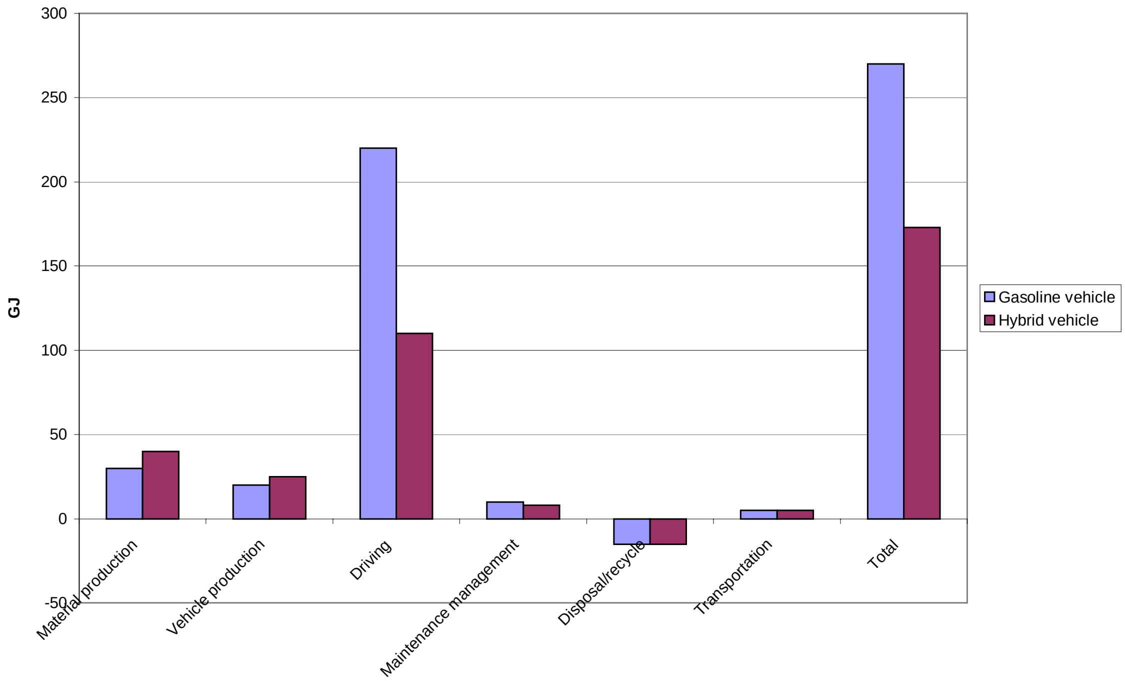
The main pollutants from automobile exhausts, for conventional gasoline and diesel engines, are carbon dioxide, carbon monoxide, nitrogen oxides, hydrocarbons and fine particles. Carbon dioxide is the most significant greenhouse gas.

Carbon dioxide emissions are directly related to fuel consumption, and for each kilometre travelled, can only be reduced by increasing vehicle efficiency, or switching to alternate fuels such as natural gas. Every 60-litre fill up at the gas station results in about 135 kg of carbon dioxide being released into the atmosphere. Globally, automobile emissions are directly responsible for close to 10% of man-made carbon dioxide emissions. If gasoline refining and processing, as well as automobile manufacturing are considered, automobiles are responsible for 15 - 20% of global carbon dioxide emissions.

One of the items in the Toyota Corporation (1998) Environmental Report is a chart, reproduced in Figure 3, that compares the life cycle analysis of the energy consumption in a typical gasoline vehicle, with that of a hybrid vehicle. The important aspect to note is that, although there is a substantial energy saving in the drive-cycle, the energy consumption in material production and in vehicle production is slightly higher for the hybrid vehicle.

Toyota have also published figures for the fuel efficiency and the CO_2 emissions (in g/km) of their vehicles in 1997. These values are based on a Japanese drive cycle that is referred to as the 10-15 mode, and is described in Appendix 1. Their hybrid vehicle, the Prius, emitted 84 g of CO_2 per km of travel, corresponding to a fuel efficiency of 28 km per litre of fuel.

Figure 3
Toyota Corporation estimates of the life-cycle analysis of their hybrid vehicle.



Source: http://www.toyota.co.jp/e/envrep98_e/contents/a/image/a05_a.jpg

The table at the lower end of Figure 4 gives passenger vehicle emissions levels for "carbon dioxide". We assume that this is a misprint. It should read "carbon monoxide".

Table 4
Emissions data for CO_2 emissions

CO_2 Emission Factor	66 g / MJ
Gasoline Energy Density	34.2 MJ / L

Source: National Greenhouse Gas Inventory Committee, 1996a

The Prius is listed as having a fuel efficiency of 28 km/L, and as emitting 84 g of CO_2/km with both of them referring to the Japanese 10-15 drive cycle, defined in Appendix 1. Multiplying the two figures yields an emission factor of 2352 g CO_2/L of fuel. If we use the energy density given in Table 4, of 34.2 MJ/L, then the emission factor for the Prius is 68.8 g CO_2/MJ, which is slightly higher than the Australian default value shown in Table 4.

These calculations again indicate that carbon dioxide emissions are directly related to fuel consumption. For each kilometre travelled, emissions can only be reduced by increasing vehicle efficiency, or switching to alternative fuels such as natural gas.

Figure 4
Toyota Corporation (1998) data for 1997 passenger cars

● **Environmental Data for 1997 New Models and Model Changes (Passenger Cars)**

		Hiace Regius		Century	Mark II Wagon	Raum	Aristo	Caldina		Prius	Harrier (*1)	Land Cruiser Wagon (*1)
Specifications	Name											
	Model	E-RCH 41W	KD-KCH 40G	E-GZG 50	E-MCV 25W	E-EXZ 10	E-JZS 160	E-ST 210G	KH-CT 216G	HK-NHW 10	GF-MCU 10W	GF-UZJ 100W
	Engine	Gasoline 3RZ-FE	Diesel 1KZ-TE	Gasoline 1GZ-FE	Gasoline 2MZ-FE	Gasoline 5E-FE	Gasoline 2JZ-GE	Gasoline 3S-FE	Diesel 3C-TE	Gasoline 1NZ-FXE	Gasoline 1MZ-FE	Gasoline 2UZ-FE
	Transmission	4AT	4AT	4AT	4AT	4AT	4AT	4AT	4AT	CVT	4AT	4AT
	Weight (kg)	1920	2050	2000	1620	1130	1640	1300	1430	1240	1670	2490
Start of Sales		Apr. 97		Apr. 97	Apr. 97	May 97	Aug. 97	Sep. 97		Dec. 97	Dec. 97	Jan. 98
Material that Destroys Ozone	CFC	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used
Gas with Global Warming Effects	HFC (g) [used in cooler refrigerants]	1150	1150	1000	850	550	600	450	450	500	650	775
	CO_2 (g/km) [10-15 mode]	284	.....	328	274	171	251	197	.....	84	251	387
Fuel Efficiency (km/l)	10-15 mode	8.3	.....	7.2	8.6	13.8	9.4	12.0	.....	28	9.4	6.1
	60 km/h Standard	14.9	17.0	12.8	15.9	21.7	16.7	22.3	21.5	.....	16.6	9.4
Noise (Acceleration noise) (dB-A)	Adapted regulation figures	78	78	76	76	76	76	76	76	76	76	78
	Other basic figures	76	76	74	75	74	75	75	75	73	75	76
Exhaust emissions(*3)	Certified as LEV Specified System (*2) [50% reduction from present regulation figures]	.....	.....	○	○	○	○	.....	.....	○	○	○
	Adapted to Future Gasoline Regulation Level [70% reduction from present regulation figures]	.....	.....	.....	.....	.....	.....	.....	.....	○	○	.....
	Adapted to Future Diesel Regulation Level	.....	.....	.....	.....	.....	.....	.....	○	.....	.....	.....
	Adapted to Present Regulation Figures	○	○	○	○	○	○	○	○	○	○	○
Substances of Environmental Concern Used in Parts	Lead	used	used	used	used	used	used	used	used	used (reduced 1/2) (*4)	used (reduced 1/2) (*4)	used (reduced 1/2) (*4)
	Mercury (discharge tube for lights)	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount
	Cadmium (electric control parts)	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount
	Sodium Azide	not used	not used	not used	not used	not used	not used	not used	not used	not used	not used	not used
Recycle (*5)	Usage of bumper recycled materials collected by dealers	○	○	○	○	.....	○	○	○	.....	○	○
	Usage of RSPP sound-proofing materials *6	.....	.....	.....	.....	.....	.....	○	○	○	.....	○

*Figures: Measured figures of the series' best-selling grade with standard specifications.

Notes:

*1 Data on and following Harrier indicate figures based on ISO 14001 which are much more strictly managed than past figures

*2 According to low-em ission vehicle certification system of 7 municipalities around Tokyo, as well as of 6 municipalities in Western Japan (Kansai area)

*3 Passenger vehicle exhaust emissions level

*4 Reduced to half of 1996 level

*5 Because there is still no clear international definition of recoverability rate, it has not been indicated in this report. Toyota, however, is moving to set standards of its own and is moving to improve vehicle recoverability.

*6 RSPP (Recycled Sound-Proofing Products) is a soundproofing material recycled from shredder residue.

Passenger Vehicle Emissions Level (10-15 mode)	Gasoline			Diesel		
	Present Regulation Figures	LEV Specified System	Future Regulation Figures	Present Regulation Figures Small-type	Present Regulation Figures Medium-type	Future Regulation Figures (Long-term Regulation)
Carbon Dioxide (g/km)	2.1	2.1	0.67	2.1	2.1	2.1
Hydrocarbon (g/km)	0.25	0.25	0.08	0.4	0.4	0.4
Nitrogen Oxide (g/km)	0.25	0.12	0.08	0.5	0.6	0.4
Particulate Matter (g/km)	.....	.....	.....	0.2	0.2	0.08

One of the most noticeable differences is in the estimate of the total life-cycle energy consumption of a Japanese gasoline vehicle, which is about 270 GJ and the estimate of the total life cycle energy consumption of the Golf III, which is 540 GJ. Part (but not all) of this discrepancy is due to the shorter assumed life of the Japanese vehicle (98,000 km) compared to the European vehicle (150,000 km). However, as shown below, the mileage is not sufficient to account for the discrepancy. The assumed fuel efficiency of the generic Japanese gasoline vehicle must be superior to that of the Golf III, and the figures that are available to us confirm this assumption. The caption of Figure 1 notes the fuel consumption of the Golf III to be 8.1 L/100 km, which is equivalent to 12.3 km/L. Figure 3 lists fuel efficiencies of new Toyota vehicles, and only the Landcruiser has a fuel efficiency lower than that of the Golf III. We suspect that the Golf III fuel efficiency and life-cycle estimates are based on an urban drive cycle, whereas the Toyota fuel efficiency and life-cycle estimates are based on the Japanese 10-15 drive cycle, which is a mixed urban and highway cycle. For comparison, Table 5 provides fuel consumption figures for an Australian car, the Holden Commodore VT Executive, as provided by the Royal Automobile Club of Queensland (1999). Comparison between the Golf III values and those in the table indicate that the quoted fuel consumption is intermediate between the city and highway cycles of the Commodore and because the Golf III, at 1025 kg, is lighter than the Commodore (1551 kg) we will assume that the quoted fuel consumption of the Golf III refers to an urban cycle, and infer a fuel consumption for the Golf III of 4.8 L/ 100 km for a highway cycle.

Table 5
Fuel consumption (L/100 km) for Holden 1998 VT Commodore Executive

	Manual	Automatic
City Cycle	11.0	12.0
Highway Cycle	7.2	7.2

Source: Royal Automobile Club of Queensland (1999)

The differences in weight, and in assumed life, play an important role in the energy estimates for the car. Fewchuk et al. (1998) have examined the life-cycle energy analysis of the original concept car and compared it to the life-cycle energy consumption associated with an upper-medium class Australian car (a Ford Falcon), with a mass of 1750 kg driven over 225,000 km. They estimate the total life-cycle energy consumption of the upper-medium class car to be 1637 GJ. This corresponds to about 1200 GJ if based on 150,000 km. This is about five times the estimate for the Japanese Prius, and about twice the estimate for the Golf III.

It is not, however, clear that the life-cycle calculations of the European and Japanese groups use the same system boundaries as the Australian group. Fewchuk et al. (1998) include fuel processing, which they estimate to be 21% of the total life-cycle energy, in their calculations whereas it appears that the European groups do not. If we remove fuel processing then the Australian estimate of fuel utilisation, which is only 60% of total life-cycle energy, increases to 75%, which is comparable to the 80% estimated by the Europeans.

3.1 The Concept Cars

The Australian Government helped to fund a project to demonstrate Australian capabilities in automotive design and engineering. The project was to design and build an Australian Concept Car, which was called the aXcessaustralia car. It was launched in February 1998. This first car was a conventionally powered car that displayed the innovation Australian carmakers and component manufacturers can exhibit. Fewchuk et al. (1998) estimated the life-cycle energy consumption of this first Concept Car to be 1396 GJ, accompanied by the emission of 126.5 Gg of CO_2.

The second aXcessaustralia Concept Car (aXcess2, or aXcess HEV) is a low emission vehicle based on a common compact sedan with supercapacitors developed by cap-XX Pty Ltd. and CSIRO, novel valve-regulated, lead-acid battery technology, as well as innovative switched-reluctance electric motors. Brief information may be found on the web at www.radial.com.au/axcess2.htm, whereas Lamb (2000a) provides more detailed information.

Parallel with the aXcess2 project, Holden and CSIRO developed a hybrid-electric car that approached the hybrid electric challenge from a different perspective. The Holden hybrid car uses a Holden engine, and a slightly modified Holden Commodore body, to drive a CSIRO electric motor/generator in a parallel hybrid configuration and uses the CSIRO/cap-XX supercapacitor and lead-acid battery technology developed for hybrid cars. This is the first application of hybrid technology in a large car (Sparke, 2000; Lamb, 2000b).

3.2 Analysis

aXcessaustralia car

The results of the Toyota Prius will be taken as providing the representative energy usage for the car. The car has a mass of about 1140 kg. The Prius has a mass of 1240 kg. The car is assumed to have a fuel efficiency of 28.6 km/L. The Prius has a fuel efficiency of 28 km/L. It will, however, be necessary to transform the Japanese data and assumptions to Australian conditions.

Our reverse engineering of the values in Figure 3 indicates that the Japanese life-cycle calculations for the Prius are based on an assumed vehicle life of 100,000 km. The Prius uses 120 GJ fuel over its life (depicted as the driving energy consumption). Automotive gasoline has an energy density of 34.2 MJ/L (National Greenhouse Gas Inventory Committee, 1996a). Thus 120 GJ corresponds to 3500 L of gasoline. The data on the Prius indicate that its fuel efficiency is 28km/L. Thus 3500 L enables such a vehicle to travel 98,000 km. Such a vehicle life is very short by Australian standards. In 1995 Australian passenger vehicles drove an average distance of 14,400 kilometres (Australian Bureau of Statistics, 1997). The average age of the passenger vehicle fleet in 1995 was 10.4 years (Australian Bureau of Statistics, 1995) so an assumed vehicle life corresponding to 150,000 km seems more realistic. Thus, our estimate for the Concept Car is that the energy usage involved in driving the vehicle is 50% greater than the Toyota figure, namely 180 GJ. Our subsequent analysis will be based on this energy usage taking place over 10 years.

VT Commodore HEV

The life-cycle assessment components for the VT Commodore is taken to be analogous to that of the Golf III. The Golf III has a mass of 1025 kg compared to the estimated mass of the VT Commodore of 1000 kg plus about 450 kg for the electric power train components (as estimated by Peter Manins). The fuel efficiency for the Golf III is 12.3 km/L (urban cycle) or 21 km/L (highway cycle) compared to the estimated 25 km/L for the VT Commodore for the urban cycle.

Over 150,000 km, the VT Commodore will use 6000 L of fuel. Using the same energy density as above, the total drive cycle energy consumption of the VT Commodore is thus 205 GJ. We use this to determine the total life cycle as in Figure 2, with 79% of the energy consumption being in the drive cycle, 7% in material production, 4% in manufacturing and assembly.

It is relevant to note the superior recycling technologies that Toyota appear to have in place. The disposal of the Prius is accompanied by a saving of 20 GJ. The recycling of the Golf III is accompanied by an extra expenditure of 0.2% of the total energy consumption.

4 Method

We shall assume that all processes in the life cycle of the motor vehicle emit greenhouse gases with the same emission factor as carbon dioxide, namely 66 g CO_2/MJ (Table 4).

The method that we shall use to estimate the greenhouse-gas emissions will be a relative one. Rather than attempt to obtain an absolute number, we will estimate the life-cycle energy consumption of a vehicle in 1996, and then examine the progressive reductions in the average life-cycle energy consumption as the hybrid car replaces the existing fleet. A further assumption is that we assume that we restrict consideration to the passenger fleet, and ignore non-gasoline vehicles.

The calculations proceed by further assuming that the passenger fleet is composed of five classes of vehicles. These classes are:

1. The aXcessaustralia car.
2. A generic low consumption gasoline vehicle, whose characteristics are derived from those publicised by Toyota Corporation in Figure 3.
3. A HEV based on the VT Commodore.
4. A generic European vehicle based on the Golf III.
5. A generic high consumption vehicle, whose characteristics have been chosen so that the fleet average CO_2 emissions agree with the 1995 estimates of the Australian passenger fleet.

Table 6
Energy Consumption (GJ) estimates for the vehicle classes for Australian conditions assumed to be 150,000 km over a 10-year life.

	aXcess LEV	Gasoline vehicle	VT Comm-odore HEV	Golf III	High con-sumption vehicle+
Driving	180	360	205	426.6	1024
Material production	41	37	18.16	37.8	128
Vehicle production	24	23	10.38	21.6	75
Fuel production*	15.14	30.28	25.95	54	108
Recycling	-20	-20	0.52	1.08	-41
Maintenance management	8	9	8#	8#	32
Transportation	1	1	1#	1#	4
TOTAL	249.14	440.28	269.01	550.08	1331

*Estimated for the concept car by using the ratios from the VT Commodore estimate.
#Estimated for the VT Commodore by using the values for the Concept Car.
+The total has been allocated to the various classes on the basis of the average percentage for the four other vehicles

The total emissions from the Australian passenger car fleet can be calculated from the data given in Table 1, and from the ABS statistic that there were 8,628,806 passenger vehicles registered in Australia in 1995. On average, passenger vehicles (which include petrol, diesel and LPG vehicles) emit 4.3 tonnes of CO_2. However, this is primary fuel consumption. If we assume that this comprises 80% of the total life-cycle energy of the vehicle, then we find that, on average, each car of the Australian passenger-vehicle fleet emits 5.4 tonne CO_2 on a life-cycle basis. This corresponds to 818.2 GJ over a ten-year period.

The energy consumption for each of the five classes of vehicle is summarised in Table 6. The energy consumption of the high consumption vehicle was chosen so as to produce 5.4 tonnes as the total CO_2 emissions (Greenfleet, 1999). By comparison, the HEV emit less than 1.8 tonnes CO_2. Inclusion of greenhouse gases other than CO_2 will be deferred until the next section.

Calculations in Table 7 proceed by assuming different proportions of HEV on the road, according to the uptake rates shown in the left hand column. It is assumed that there are equal numbers of the two classes of HEV, and that government policy is such that of the remainder of the vehicles, 50% are low consumption gasoline vehicles, and the others are equally split between the high consumption vehicles and the generic European vehicle (Golf III).

Table 7
Proportions of the vehicle fleet assumed to be in the five annual energy use categories of Table 6 (left side), and calculated annual life-cycle energy consumption and carbon dioxide emission (right side). HEV are shown in italic.

	aXcess LEV	**Generic petrol car**	**VT Commodore HEV**	**Golf III**	**High Con-sumption**	**Equiv. energy**	**CO_2**	**% reduction**
GJ annually	***25***	**44**	***27***	**55**	**133**	GJ	kg	
1996	*0*	0.4	*0*	0.2	0.4	81.8	5399	
2010								
10%	*0.05*	0.45	*0.05*	0.225	0.225	64.7	4270	21
20%	*0.1*	0.4	*0.1*	0.2	0.2	60.4	3986	26
30%	*0.15*	0.35	*0.15*	0.175	0.175	56.1	3703	31
2020								
50%	*0.25*	0.25	*0.25*	0.125	0.125	47.5	3135	42
70%	*0.35*	0.15	*0.35*	0.075	0.075	38.9	2567	52
90%	*0.45*	0.05	*0.45*	0.025	0.025	30.3	2000	63
100%	*0.50*	0	*0.50*	0	0	26.0	1716	68

4.1 Other Greenhouse Gases

Methane emissions are a function of the methane content of the motor fuel, the amount of hydrocarbons passing unburnt through the engines, and any post-combustion control of hydrocarbon emissions, such as the use of catalytic converters. The use of post-combustion control reduces methane emissions, a result implicit in the data of Table 8. Nitrous oxide emissions from motor vehicles arise primarily as a result of catalysts in road vehicles.

Figure 1 illustrates that there has been a decrease in CH_4, and an increase in N_2O, emissions as catalytic converters have replaced previous emission control mechanisms. However, it is worth noting that the contribution of these two gases to the calculation of CO_2-equivalents from petrol passenger vehicles increases the emission by about 8%, on the basis of the values given in Table 1.

National Greenhouse Gas Inventory Committee (1996b) derive emission factors for petrol-driven passenger cars in terms of mass of emission per kilometre travelled. This is done because the Australian methodology for calculation of non-CO_2 emissions is based on kilometres travelled, primarily because statistics are normally provided in this way. They are not realistic when applied to low emission, or zero emission, vehicles. To estimate the non-CO_2 gases from hybrid vehicles, we note that such emissions take place only during the time that fuel is being consumed by the engine. An electrical vehicle may still travel 10,000 km but will not emit.

We assume that the emission of non-CO_2 gases depends on the amount of fuel passing through the emission control system. The increases in emissions as a result of the decay of the emission control system depend only on distance travelled by the vehicle, which is assumed to be 15,000 km per year for both conventional and HEV vehicles. In addition, we have no reasonable quantitative basis on which to estimate improvements (if any) in the CH_4 or N_2O emission characteristics of the emission control systems as more stringent emission limits apply in the future. Finally, we assume that the 80:20 split between three-way and two-way catalytic converters that has been operative since 1990 (National Greenhouse Gas Inventory Committee, 1996b) continues into the future.

Thus to allow for the effects of methane and nitrous oxide we increase fuel combustion emissions of carbon dioxide by the same factor as at present, namely 8%.

5 Batteries and Supercapacitors

Figure 5: The aXcessaustralia Battery Pack

Figure 6: One Half of the Supercapacitor Pack

5.1 Battery information

According to information provided by Russell Newnham (e-mail dated 30 September 1999 to P. Manins) the battery pack of the concept car has five, 12-V batteries. Each battery weighs 11.5 kg. Of this, 7.5 kg is lead, 2.2 kg is lead dioxide, 0.7 kg is sulfuric acid, 1.1 kg is the case and lids. There is also a small amount of glass wool separator in the batteries but this is minimal in weight and volume. The lead, lead dioxide and sulfuric acid are recyclable. There are two types of concept car being developed by two different manufacturers. Though both intend to use the same CSIRO battery packs, they have developed slightly different racks.

Holden (VT Commodore) battery housing
Titanium (in production, cheaper aluminium would be used) with an estimated weight of 8 kg.

aXcessaustralia battery rack
Magnesium (once again, if in production, cheaper materials such as aluminum would be used).

It is estimated that the life of the battery pack is such that 2 packs (i.e. 10 batteries) are needed every 100,000 km.

5.2 Supercapacitor information

According to information supplied by Tony Vassallo (e-mail dated 5 November 1999 to P. Manins) the supercapacitor pack will weigh approximately 60 kg. The materials in this pack are activated carbon (approximately 7 kg), aluminium foil (approximately 10 kg), electrolyte (approximately 15 kg) of tetraethylammonium tetrafluoroborate in acetonitrile, and a microporous separator. The supercapacitors will be maintenance free, and have a 4000 hour operating life, which should last the life of the car.

5.3 Life-cycle estimate

In a conventional car, the cost of a battery is approximately 0.5% of the cost of the vehicle. This provides a first order approximation to the likely life cycle energy involved in the battery. Tony Vassallo (e-mails dated 13 April and 29 May 2000 to T. Beer) estimates that 70 kg of CO_2 is emitted in the manufacture of a conventional 0.7 kWh battery. The HEV batteries are about 0.25 kWh, so that about 27.5 kg of CO_2 is emitted during their manufacture. Having a bank of five such batteries will increase the energy requirements compared to a conventional vehicle, but we assume that the life-cycle calculations for the Prius have already taken such factors into account to arrive at the higher energy usage in manufacturing of the Prius compared to a conventional vehicle.

The situation with respect to the supercapacitor (which is not a part of the Prius) will be different. The manufacture of aluminium emits substantial quantities of greenhouse gases, especially during aluminium smelting when electric currents are used to electrolyse carbon blocks. During this process there are direct emissions of carbon dioxide from the carbon blocks, indirect emissions as a result of the generation of the electricity, and in addition if there are operating problems then quantities of perfluorocarbon will be emitted.

Tony Vassallo estimated the costs of a supercapacitor pack to be about US$1200 when manufactured in volume. This is about 6% of the cost of a VT Commodore Executive. As a first approximation, we will assume that the life-cycle greenhouse-gas emissions associated with the supercapacitor increase the emissions from the HEV by 6% over a 10-year life, or 0.6% per year.

5.4 Battery maintenance

According to information provided by Russell Newnham (e-mail dated 30 September 1999 to P. Manins) the batteries will require equalisation charging once every two weeks to one month. This, however, will require minimal power and will not be a significant power cost (~2-4 kWh per two weeks). The batteries will require a check and clean on a regular basis (once every 6 months to 1 year).

The use of electricity to recharge a battery greatly increases the life-cycle greenhouse-gas emissions from a hybrid vehicle. The reason for this is that most Australian electricity is produced by burning coal.

Table 8
Greenhouse-gas emissions (kg CO_2-equivalents per kWh) from the use of electricity in various parts of Australia

Location	Greenhouse-gas emissions
Northern Territory	0.69
New South Wales	1.04
Victoria	1.39
Queensland	1.01
South Australia	0.98
Western Australia	1.10
Tasmania	0.06

Source: Sustainable Solutions, 1995

Table 8 shows the greenhouse gases produced for each kilowatt-hour of electricity consumed. In Victoria, 1.39 kg of greenhouse gas is produced for each kilowatt-hour of electricity consumed because Victoria primarily uses brown coal to generate electricity (Sustainable Solutions, 1995). In Tasmania, where there is substantial hydro-electric supply of electricity, only 0.06 kg of greenhouse gases are emitted for each kilowatt-hour of electricity that is used.

It is presently unclear how much domestic electricity will be used to recharge and maintain the batteries. Estimates of battery charge rates have ranged from a low of 3 kW to a high of 10 kW (Gates and Westcott, 1998). We expect that in most situations the batteries will be recharged during driving. However, even the minimal power involved in battery equalisation is associated with significant greenhouse-gas emissions. If 4 kW-hour of electricity is used every two weeks to charge the batteries of a vehicle in Victoria, then over a year 143 kg of CO_2 is emitted. This is approximately 8% of the estimated 1.8 tonnes CO_2 that we estimate to be the HEV emissions.

This document will examine two scenarios with respect to battery charging. The first scenario is the one in which most battery charging is accomplished during the normal driving of the HEV/LEV, and electrical charging takes place every two weeks. The results of this scenario are given in Table 9. The second scenario is one of complete electrical use with charging of the battery accomplished by using electricity. It will further be assumed that any electricity that is used is sourced from Victorian brown coal.

Table 9
Predicted annual energy consumption, greenhouse-gas emissions and relative greenhouse-gas reductions for various HEV uptake rates when non-CO_2 gases and minimal battery charging are included.

HEV uptake rates	Equiv. Energy	CO_2	CO_2-equiv	Super-capacitor CO_2-equiv	Battery maintenance CO_2-equiv	Total CO_2-equiv	% reduction
	GJ	kg	kg	kg	kg	kg	
1996	82	5399	5825	0	0	5825	
2010							
10%	65	4270	4607	1	14	4622	21
20%	60	3986	4301	2	29	4332	26
30%	56	3703	3995	3	43	4041	31
2020							
50%	48	3135	3382	5	72	3460	41
70%	39	2567	2770	7	101	2878	51
90%	30	2000	2158	9	129	2296	61
100%	26	1716	1851	11	143	2006	66

5.5 Battery charging comparison

The calculations in Section 5.4, and the values in Table 9, indicate that electrical charging of batteries may lead to significant greenhouse-gas emissions, depending on the source of fuel to generate the electricity. Indeed, it raises the specific question: how does electric charging of a battery compare with charging a battery by using petrol while driving a car around.

Table 8 gives the greenhouse-gas emissions per kilowatt hour. To compare this with the use of petrol (by driving a car) for charging a battery, we need to estimate the greenhouse-gas emissions per unit of energy for automobiles. The National Greenhouse Gas Inventory Committee (1996b) default value for CO_2 emissions is 66 g/MJ, which corresponds to 237.6 g/kWh. The emissions of the other greenhouse gases will increase this value, and Sustainable Solutions (1995) estimate it to be 258.9 g CO_2-equivalents/kWh.

However, the values for petrol tat have just been quoted refer to the gross calorific value. According to the values quoted by Sparke (2000) only 38% of this energy is available to power the battery. Thus the above emissions, in terms of calorific value, need to be multiplied by 2.63 to estimate the greenhouse-gas emissions corresponding to battery charging using petrol. This comes to 681 g CO_2-equivalents/kWh.

Comparing this value of 0.68 kg CO_2-equivalents/kWh with the values in Table 8, we observe that in most Australian States petrol charging of a battery emits less greenhouse gases than electrical charging. The ratios are calculated and depicted in Table 10. In Victoria charging an automobile battery using electricity emits 2.04 times the greenhouse gases that charging the battery using petrol would emit. By contrast, in Tasmania, which derives much of its electricity from hydro-electricity, electric charging emits less greenhouse gases than petrol charging.

Table 10
Ratio of greenhouse-gas emissions from the use of electricity to the emissions from the use of petrol to charge automobile batteries.

Location	Greenhouse-gas emissions
Northern Territory	1.01
New South Wales	1.53
Victoria	2.04
Queensland	1.48
South Australia	1.44
Western Australia	1.62
Tasmania	0.09

Even though the electricity industry is undergoing substantial change as a result of electricity reform and the development of a national market with pooled prices, the resulting price volatility does not affect the retail purchaser of electricity. A typical tariff is that of United Energy in Victoria, who charge domestic users 11 c/kWh for the first 1020 kWh, then 12.52 c/kWh. Their night rate is 4.47 c/kWh.

Petrol has an energy density of 34.4 MJ/L (National Greenhouse Gas Inventory Committee, 1996b), but as previously indicated, only 38% of this energy is available for charging the battery. Thus each litre of petrol can provide 3.61 kWh with which to charge the battery. At a typical retail petrol price of 80 c/L, petrol charging of a battery costs about 22.1 c/kWh. This is about double the cost of charging a battery using electricity at the standard domestic tariff, and about five times the cost of using a night-tariff.

6 Discussion and conclusions

Table 9 calculates the expected greenhouse gas reductions for various HEV uptake rates, and for minimal battery recharging. These calculations extend the values in Table 7 to allow for the incorporation of non-CO_2 gases, and allowance is made for supercapacitors, and battery recharge and maintenance. The greenhouse-gas emissions associated with vehicle disposal have been treated as zero. The reason for this is that it is uncertain how to analyse the material and energy substitution as a result of recycling the materials in the vehicle when it is disposed. Toyota (Figure 3) claim an overall energy credit for this. Volkswagen (Figure 2) treat it as an energy debit. We have thus treated it as zero.

Table 11 considers the greenhouse gas emissions when the HEV/LEV is driven primarily on batteries. The method used to quantify the emissions is to assume that the energy involved in the combustion of 80% of 1851 kg of CO_2-equivalents is produced from Victorian brown coal. This corresponds to 3021 kg of CO_2-equivalents – which is obtained by multiplying the previous number by 2.04. Thus the greenhouse gas emissions from a standard passenger vehicle are taken as 5825 kg CO_2-equivalents, whereas the greenhouse gas emissions from the HEV/LEV are taken as 3021 kg CO_2-equivalents (used to charge the batteries), 370 kg from the manufacture of the vehicle, plus another 11 CO_2-equivalents to allow for the super-capacitor.

Table 11
Predicted annual energy consumption, greenhouse-gas emissions and relative greenhouse-gas reductions for various HEV uptake rates when non-CO_2 gases and maximum battery charging are included.

HEV uptake rates	CO_2 from HEV other than usage	CO_2-equiv from petrol vehicle	Super-capacitor CO_2-equiv	Battery maintenance CO_2-equiv	Total CO_2-equiv	% reduction
	kg	kg	kg	kg	kg	
1996	0	5825	0	0	5825	
2010						
10%	37	5243	1	302	5583	4
20%	74	4660	2	604	5340	8
30%	111	4078	3	906	5098	12
2020						
50%	185	2913	5	1510	4614	21
70%	259	1748	7	2115	4129	29
90%	333	583	9	2719	3644	37
100%	370	0	11	3021	3402	42

The analysis of Tables 7, 10 and 11 averages the emissions from the whole vehicle fleet into an equivalent emission for a single vehicle. This method of analysis is well-suited to examination of the percentage reduction in greenhouse-gas emissions as there is increasing uptake of HEV/LEV vehicles. It does not, however, deal with the total greenhouse-gas emissions to be expected as a result of the growth of the total vehicle fleet.

There are three impediments to the uptake of HEV/LEV vehicles: availability, price and consumer resistance. There are encouraging signs that all three of these impediments are being eroded as a result of increasing community interest in, and concern for, environmental issues related to greenhouse gases and air quality. The Government is committed to meeting Euro3 emission standards by 2007, and it is probable that Euro4 standards will become mandatory some time after that. Such stringent emission controls, which HEV/LEV cars can meet, will make them attractive propositions for consumer purchase, provided that they are priced accordingly. Without government intervention we estimate a 10% uptake by 2010 increasing to 50% by 2020. With active government intervention these figures could be as high as 30% by 2010, and 90% by 2020.

The main conclusions to emerge from this analysis are that:

- An average Australian passenger car emits 5.8 tonnes CO_2-equivalents per annum on a life cycle basis.
- A typical HEV emits 2.0 tonnes CO_2-equivalents per annum on a life cycle basis, if the batteries are charged during the normal driving of the vehicle. This is a 66% reduction in greenhouse gases compared to the average Australian passenger car.
- A completely electric vehicle (charging via Victorian brown coal) has life-cycle emissions of 3.4 tonnes CO2-equivalents per annum. This is a 42% reduction in greenhouse gases compared to the average Australian passenger car.
- The dominant greenhouse-gas emissions from motor vehicles manifest themselves in the CO_2 emitted during the combustion of the motor fuel.
- The other greenhouse gases, CH_4 and N_2O, contribute about 10% of the greenhouse-gas emissions from a motor vehicle, when expressed in CO_2-equivalents based on 100 year global warming potentials.
- Life-cycle analyses of hybrid vehicles indicate that fuel combustion comprises about 80% of the total energy consumption.
- There are significant greenhouse-gas emissions associated with battery charging in all Australian States except for Tasmania. Even 4 kW-hour every two weeks can increase greenhouse-gas emissions associated with the vehicle by up to 8%. Exclusively using Victorian electricity to charge the batteries will increase greenhouse gas emissions almost doubles the greenhouse gas emissions from the HEV/LEV.
- In all Australian States, except for Tasmania, recharging the battery using electricity emits more greenhouse gases than recharging the vehicle by driving it and consuming petrol. In Victoria recharging the battery emits twice the greenhouse gases, but even at the domestic electricity tariff costs only half that of using petrol to recharge the battery.
- The use of the HEV/LEV will reduce greenhouse-gas emissions from passenger vehicles. If 90% of the vehicle fleet consists of HEV/LEV vehicles then we estimate greenhouse-gas emissions from petrol-driven passenger cars to reduce by 61%.

6.1 Uncertainties

It is difficult to calculate accurate life-cycle energy consumption for a vehicle that is in production. It is therefore even more difficult to obtain estimates for a vehicle in the design stage. However, enough work has been done in Europe and Japan that the proportion of energy involved in the major stages of the vehicle manufacture, transport, usage, and disposal may be inferred. Exact figures depend on the way in which the vehicle will be used.

Because of these uncertainties, we devised a method that estimated a representative greenhouse-gas emission for a vehicle – representing the whole vehicle fleet - and estimated the reduction in the emission as the fleet composition changed. Though one may dispute the actual figures (which may be uncertain to ±50%), we attribute far less uncertainty to the estimates of greenhouse-gas reduction, which are based on relative estimates rather than absolute estimates.

The uncertainties associated with the greenhouse-gas reductions are dependent on the assumptions made about the proportions of non-HEV vehicles within our three representative classes. We have assumed that government policy as a result of the commitments emanating from the Kyoto protocol will encourage low consumption vehicles. Accordingly, it is assumed that the greatest relative decline is in the high consumption vehicles. If this is not the case then the greenhouse-gas reductions will be less. For example, if a 90% uptake of HEV is accompanied by 10% uptake of high consumption vehicles then the greenhouse-gas reduction drops from 61% to 54%.

We also note that the assumption that battery recharging takes place during utilisation of the HEV/LEV plays a key role. If it is assumed that the batteries are charged solely from electricity derived from Victoria, then the estimated 61% reduction in greenhouse gases from passenger vehicles becomes only about 37%.

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Appendix 1
10-15 mode drive cycle

10-Mode Cycle

Urban driving cycle used for light-duty vehicles, later replaced by the 10-15 mode cycle. It represented a route of 3.32 km, completed in 675 s. The maximum speed is 40 km/h.

10-15 Mode Cycle

Urban driving cycle that is currently used in Japan for emission certification of light-duty vehicles. It is derived from the 10-mode cycle by adding another segment of a maximum speed of 70 km/h. The total distance is 4.16 km, completed in 660 s.