A HIGH RESOLUTION CHEMICALLY REACTIVE NEAR-FIELD DISPERSION MODEL. PART 2: APPLICATION IN AN INTELLIGENT TRANSPORT SYSTEM

Martin Cope[1], William Lilley[2], Leorey Marquez[3], Nariida Smith[4], Sunhee Lee[1]
CSIRO Energy Transformed Flagship, [1]PVB1 Aspendale VIC, 3195, Australia; 2PO Box 330, Newcastle, NSW, 2300, Australia; [3]PO Box 56, Highett, VIC, 3190, Australia; [4]PO Box 310, North Ryde, NSW 1670, Australia

Abstract

As part of the Low Emission Transport theme of the CSIRO Energy Transformed Flagship we are developing an Intelligent Transport System (ITS) "Greenhouse Gas (GHG)/ Energy Impact Evaluation Tool" (ITS–GHG tool). This tool will be used to demonstrate to stakeholders the environmental (and ultimately cost) benefits of adopting Intelligent Transport Systems as a method of optimising traffic movement within a metropolitan road transport grid.

The prototype ITS–GHG tool consists of a transport network model, a vehicular emissions module; a prognostic weather–chemical transport modelling system for modelling urban-scale air quality impacts; a high–resolution reactive plume model for simulating near–road air quality; and population exposure methodology for modelling changes in mortality in response to the adoption of an ITS strategy.

Operation of the prototype ITS–GHG tool is demonstrated for the Sydney metropolitan road network. The tool is used to generate traffic movements and air pollutant emissions for a 1996 base case (business-as-usual) and a 'better traffic management' (BTM) scenario. In this paper we particularly emphasise the outcomes of high–resolution near-road air pollution modelling as this demonstrates the operation of the Lagrangian Wall Model (LWM), a new model which we have recently developed for simulating the impact of ITS and related transport applications.

Keywords: traffic, air pollution, near-road, population exposure, intelligent transport system

1. Introduction

Recent advances in transport, computing and communications technologies have given rise to a new range of tools called Intelligent Transport Systems (ITS). This is the term commonly used to describe the use of electronic systems for the management of road traffic and other modes of transport to improve decision making by network operators and users[1]. Such systems are used to maximise road network efficiency through the continuous monitoring of traffic conditions, through the coordination of traffic lights, through the use of electronic tolling devices and through the provision of real–time information to drivers on travel times and optimal travel routes. In addition to maximising network efficiency ITS has a number of environmental benefits, particularly with respect to reducing greenhouse gas (GHG) and air pollutant emissions.

ITS has been heavily adopted in the U.S.A, Europe and Japan and has been shown to yield measurable improvements in traffic efficiency, leading to increases in mean travel speed, reduced numbers of delays, reduction in travel time, fuel consumption and GHG and air pollutant emissions (see Table 1).

As part of the Low Emission Transport theme of the CSIRO Energy Transformed Flagship we are undertaking the development of an (ITS) "(GHG)/ Energy Impact Evaluation Tool" (ITS–GHG tool). This tool will be used to demonstrate to stakeholders the environmental (and ultimately cost) benefits of adopting ITS as a method of optimising traffic movement within a metropolitan road transport grid.

[1] http://www.kent.gov.uk/sp/roads/inteltrans.html

Table 1. Examples of ITS impacts on travel time, fuel consumption and emissions

Application	***ITS Deployed***	***Delay/Travel Time Impact***	***Speed/VKT Impact***	***Fuel/emissions impact***
ITS America http://www.itsa.org/	Computer-coordinated traffic system	Cut delays by 37%	Increased travel speed by 22%	Cut CO emissions by 12%
MMDI Seattle http://www.itsdocs.fhwa.dot.gov	Incorporating information on arterial traffic flow into ATIS	1.8% reduction in vehicle delay	5.6% reduction in number of stops	2% reduction in vehicle emissions
ITS Toronto http://www.itsdocs.fhwa.dot.gov	SCOOT (**S**plit **C**ycle **O**ffset **O**ptimisation **T**echnique	8% reduction in travel time. 17% decrease in vehicle delay	22% reduction in number of stops	5.7% decrease in fuel consumption, 5% decrease in CO emissions
Helsinki http://lipasto.vtt.fi/yksikkopaastot/vemosim.htm	VEMOSIM simulation model			3.6% decrease in fuel consumption, 4.9% decrease in CO

In the next section, we provide a description of the systems which make up the ITS–GHG tool. This is followed in Section 3 by a discussion of the results pertaining to the implementation of a Better Traffic Management scheme (BTM) to metropolitan Sydney. Particular emphasis is given to near-road pollutant impact simulations undertaken using a newly developed Lagrangian modelling system.

2. Methodology

The prototype ITS–GHG tool consists of the TransCAD GIS Modelling Package[2] for modelling traffic movement, a vehicular emissions module; a prognostic weather–chemical transport modelling system (TAPM; Hurley 2002) for modelling urban-scale air quality impacts; a Lagrangian reactive plume model (LWM; Lilley and Cope 2005) for modelling near–road air quality; and a module for estimating changes to population mortality in response to changes in short-term air pollutant exposure. Each of these components is now considered in more detail.

2.1. Network Transport Modelling

This component of the ITS-GHG tool uses the TransCAD system to model network flows for business-as-usual and ITS traffic scenarios. TransCAD includes a suite of traffic assignment models which can be used to estimate flow patterns. TransCAD also includes a multi-modal traffic assignment procedure for simultaneously assigning cars, trucks and buses to a road network.

The following information is required to generate traffic flow predictions. 1/ A table of vehicle types and attributes; 2/ A network of road links and their attributes (such as vehicle capacity)- see Figure 1 ; 3/ An origin–destination trip matrix (i.e. number of trips taken between defined start and end points in the metropolitan region) ; 4/ A table defining the origin–destination zones. Given this information, TransCAD is able to calculate the total number of vehicles which traverses each link, the time taken to traverse each link and the volume to capacity ratio for each link. This information is available for each vehicle type, for different periods of the day (i.e. A.M. peak; P.M. peak, midday and night).

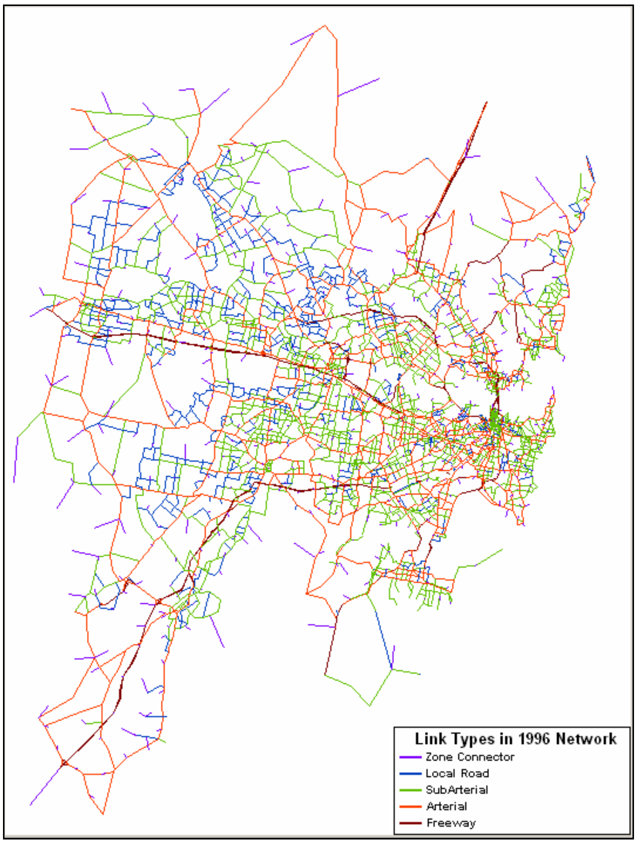

Figure 1. Base case network of 15000 one-way links for the Sydney metropolitan area.

[2] http://www.caliper.com/tcovu.htm

2.2. Link Emissions Modelling

Using this module, fuel use, GHG and air pollutant emissions, for each link in the road network are estimated, taking into account the mix of traffic, an estimated distribution of fuel types, the speed of traffic and the loadings of commercial vehicles. In particular, link–level emission rates are calculated as follows.

$$q_k = \sum_i \sum_j V_{ij} \times EF_{ijk} \times SCF_{ij} \times LCF_{ij} \times L \qquad (1)$$

where q_k is the emission rate for pollutant *k* (g h^{-1}), V_{ij} is the number of vehicles of type *i* and fuel type *j* on the link, $EF_{i,j,k}$ is the emission factor for pollutant *k*, SCF_{ij} is a speed correction factor, LCF_{ij} is a load correction factor for commercial vehicles and *L* (km) is the link length.

The module is used to calculate the emissions of greenhouse gases (i.e. carbon dioxide, nitrous oxide) and air pollutants (including carbon monoxide, volatile organic compounds, oxides of nitrogen, PM_{10}, benzene and butadiene) for the prescribed ITS scenarios. An example of the relative spatial distribution of PM_{10} emissions for Sydney for the A.M. traffic peak is shown in Figure 2.

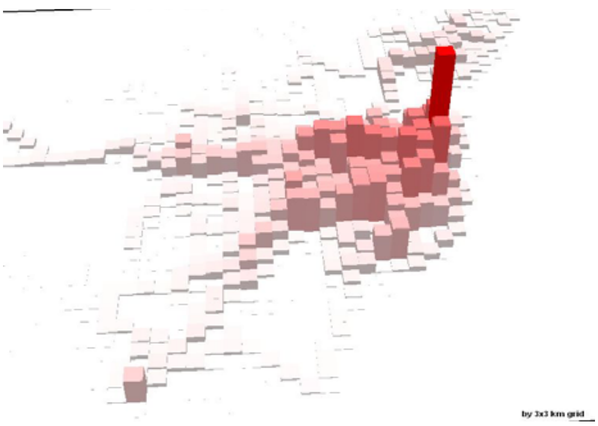

Figure 2. Block plot showing the relative spatial distribution of A.M. peak PM_{10} emission rates from the Sydney metropolitan road network.

2.3. TAPM Urban Airshed Modelling

TAPM (Hurley 2002) is a combined weather prediction and chemical transport modelling system. TAPM solves the governing equations of mass, momentum, energy, moisture and scalar transport on a series of user defined, nested grids. Initial and boundary conditions for the meteorological fields are provided by a large scale analysis, generated by the Bureau of Meteorology. The system is able to simulate the transport of tracers, primary particles, and a simple photochemical system including sulphate and nitrate for a variety of source characteristics. The system is run for periods of days to years.

Within the ITS–GHG tool TAPM is used to predict urban scale (i.e. grid spacing of 1–2 km) ground-level pollutant concentrations resulting from the combined impact of link emission sources generated by TransCAD and the emissions module, and other non-vehicular emissions (such as commercial and domestics sources).

2.4. LWM Near–Road Modelling

The Lagrangian Wall Model (LWM) is a fine-scale dispersion model which has been developed to assess the near-field impact of line, area and point sources, which themselves may be imbedded within a larger scale concentration field (Lilley and Cope 2005).

The model consists of a two-dimensional wall of cells which moves in very high resolution spatial steps (typically 10 m) through a region of interest at a speed governed by the vertically averaged wind. The wind fields, the initial concentrations across the ‘wall’ (specified upwind of the region of interest), and boundary conditions at the edges of the wall, are prescribed from the TAPM concentration fields. As the wall is advected through the region, the LWM’s fine resolution is able to resolve emissions from such small-scale features as roads, industrial point sources and tunnel stack vents.

2.5. Calculation of Population Mortality

In addition to calculating the change in ground–level concentrations of key air pollutants, it is also useful to estimate how the implementation of an ITS strategy will vary air pollution–related rates of mortality. In this respect we can draw on a considerably body of epidemiological research (i.e. see the review by Brunekreef and Holgate 2002 and references therein) which relates short term (i.e. hours to days) variations in air pollution concentrations to daily changes in the rate of population mortality. An outcome of this research is the development of relative risk functions (RR) which provides a relationship between a quantum change in pollutant concentration and change in population mortality rate.

$$D_{CO} = Po * (RR-1), \qquad (2)$$

where D_{CO} = the increase over a baseline mortality for a unit increment in a designated air pollutant; P_0 is the baseline mortality of the population in the absence of the air pollutant and *RR* is the relative risk function

It then follows that the total increase in mortality as a result of the pollutant exposure is given by the following:

$$N = D_{CO} * (C_{24} – C_t) \times P \qquad (3)$$

where C_{24} is the 24 h pollutant concentration, C_t is a threshold concentration below which no health effect is observed and P is the population of the studied region.

3. Example of an ITS-GHG application

In order to demonstrate the use of the ITS–GHG tool, we consider the impact on CO and PM_{10} concentrations and related population mortality, of introducing a “Better Traffic Management” (BTM) system into the Sydney metropolitan region. According to this scenario, the introduction of a suite of ITS strategies on arterial roads in Sydney will result in higher traffic speeds (3 km h^{-1} faster at road saturation point), and will also enable 10% more traffic to be added to each arterial road before saturation is reached.

The ITS–GHG tool has been used to model the vehicle network volumes, vehicular emissions and the resultant ground–level concentrations and levels of mortality for a base case and the BTM scenario. Because we particularly want to demonstrate the use of the newly developed LWM, we will concentrate, in the example that follows, on a segment of arterial road in Sydney–Victoria Rd., which runs to the north–west between Rozelle and Westmead (see Figure 3).

3.1. Transport Network Modelling

The base case and BTM traffic scenario was generated from data for 1996 vehicle movements in metropolitan Sydney according to the procedure described in Zito and Taylor (2003). In particular, the TransCAD modelling is based on recent NSW Transport Data Centre data and models which provide:

1. A subset of the 1996 Sydney road network, consisting of 15,000 one-way links and excluding local roads.
2. A 1996 matrix of origin destination pairs for passenger vehicles and 3 categories of freight vehicles (articulated trucks, rigid trucks and light commercial vehicles) at detailed travel zone level.

For the base case, simulated traffic volumes were compared with published counts for roads comprising major screenlines and were found to deviate by at most 6% (Smith and Kilsby 2003).

3.2. Emissions Modelling

The link emissions module was applied using the base case network data and the resultant emission rates (and fuel usage totals) were found to conform to published aggregates for the region (Zito and Taylor 2003).

By way of example, the total daily emission rates for Victoria Rd. for the base case and for the BTM scenario are given in Table 2 for four different air pollutants. It can be seen that the effect of the BTM scenario is to reduce emission rates by up to 6%. Additionally, emissions from non-motor vehicle sources, taken from the Metropolitan Air Quality Study air emissions inventory (Carnovale et al. 1996), were also incorporated, thus providing an estimate of the total urban emission loadings for the air quality modelling.

Table 2. Mass emissions (kg/day) for Victoria Rd. Sydney for two emission scenarios

	CO	***VOC***	***NO_x***	***PM_{10}***
Base case	11119.9	1764.5	1519.1	45.6
BTM	10462.6	1676.1	1457.7	43.0
∆%	-6.3	-5.3	-4.2	-5.9

3.3 Urban Scale Pollutant Concentration Modelling

Using the combined urban scale emissions, TAPM was run for the year 2001, generating hourly concentration predictions for (in this example) carbon monoxide and PM_{10} for a 2 km resolution grid which covered metropolitan Sydney. An example of the predicted concentration field for carbon monoxide (24 h average) is given in Figure 3 for a winter day. Note that only a sub-set of the urban grid, which is centred on Victoria Rd. is shown in this example. It can be seen that the CO increases in concentration when moving towards the southeast of the sub-domain (peak CO concentrations of 0.6 ppm are predicted in this region).

The TAPM concentration predictions generated using the base case and BTM emission scenarios may then be used to estimate the urban–scale impact of the ITS scenario for each of the modelled pollutants.

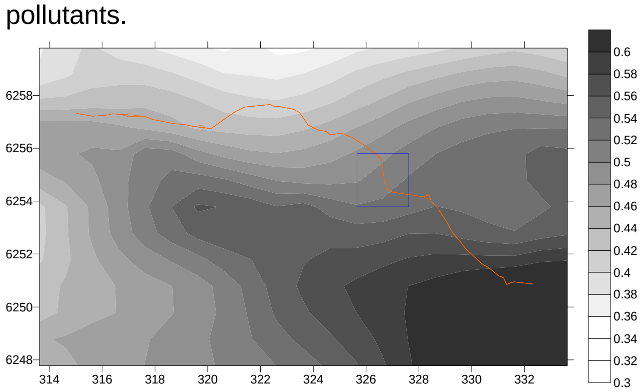

Figure 3. Plot of TAPM modelled 24 h average CO concentration (ppm) within the vicinity of Victoria Rd.

3.4 Near–Road Pollutant Concentration Modelling

The procedure for using the Lagrangian Wall Model for estimating near–road pollutant concentrations is discussed in Lilley and Cope

(2005). Briefly, three stages are involved: 1/ TAPM wind fields are used to calculate air parcel trajectories which, in the example considered here are "anchored" to 34 points spanning the length of Victoria Rd. The air parcel trajectories are calculated once per hour and extend forward and backwards in time and space from the anchor point (see Figure 4).

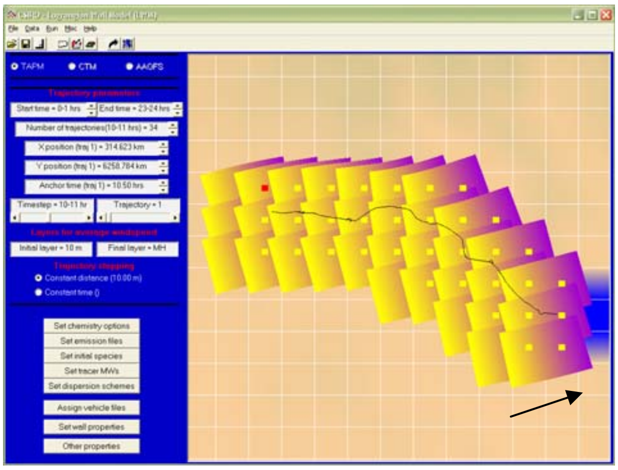

Figure 4. Showing the area covered by the Lagrangian Wall model for 34 trajectories which cover the length of Victoria Rd (line). The arrow indicates the direction in which the "walls" are moving for this particular hour. Each square represents a TAPM 2 x 2 km^2 urban cell.

2/ once the trajectory has been established, TAPM pollutant concentration predictions are interpolated to the starting position of each wall. Emissions and meteorological variables (i.e. temperature, mixing height etc.) are interpolated to the time and position of each wall; 3/ a diffusion–chemistry equation is integrated, yielding pollutant concentration predictions at a horizontal resolution of 20 m (in this example).

For example, the predicted near-road 24 h CO concentrations for one segment (see Figure 3) of Victoria Rd are shown in Figure 5 for the base case and for the difference between the BTM and base case scenarios (BTM–base case).

Close to the road it can be seen that the 24 h CO concentrations are predicted to reach 2.5 ppm, or more than five times the urban scale concentrations predicted using TAPM. With regard to the BTM ITS scenario it can be seen that the improved traffic flow results in a reduction (of up to 0.25 ppm) in the 24 h CO concentrations within the vicinity of Victoria Rd within this cell.

3.5. Mortality Modelling

The TAPM and LWM air pollutant concentration predictions can be used to estimate mortality changes according to the methodology outlined in Section 2.5. We again consider Victoria Rd. and this time consider 24 h average predictions of PM_{10} concentration. For the purposes of demonstration we define the baseline mortality rate to be the Australia-wide death rate from non-accidental causes for 2002- 18 deaths per million people per day (ABS 2004). Following NEPC (2002), we prescribe an all age group short term residual risk (RR) of 1.01% increase in population mortality per 10 $\mu g\ m^{-3}$ increase in 24 h PM_{10} concentration and, additionally assume a zero concentration threshold.

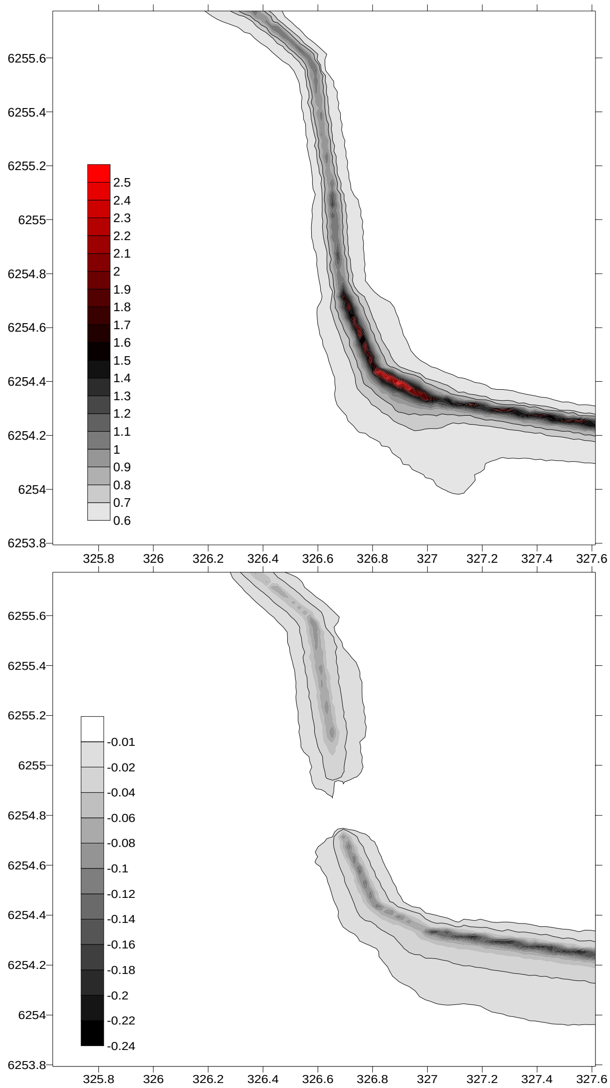

Figure 5. Predicted near-road 24 h CO concentrations (ppm) for a segment of Victoria Rd (see Figure 3).Top- base case; Bottom– difference between BTM and base case.

Using these data, the near-road predicted 24 h PM_{10} concentration and a gridded population data base, mortality rates and changes in mortality rates as a result of the PM_{10} emissions from vehicles on Victoria Rd can be predicted as shown in Figure 6. Considering Figure 6–top it can be seen that PM_{10} mortality rates are predicted to lie in the range 1–12x10^{-4} deaths per km^2 per day for the base case.

The ‘tiled’ distribution of mortality results from the use of a relatively coarse 2x2 km^2 population data base– a shortcoming which will be improved as the GHG–ITS tool is further developed.

Considering Figure 6–bottom, it can be seen that the effect of the BTM ITS scenario is to reduce mortality rates by about 1% away from the road (due to reductions in background PM_{10}) and by up to 15% close to the southern section of the road (note that this is larger than the mean level of reduction of PM_{10} emissions for Victoria Rd., shown in Table 2, because the resultant change in traffic flow when going to the BTM scenario is not uniform along the road).

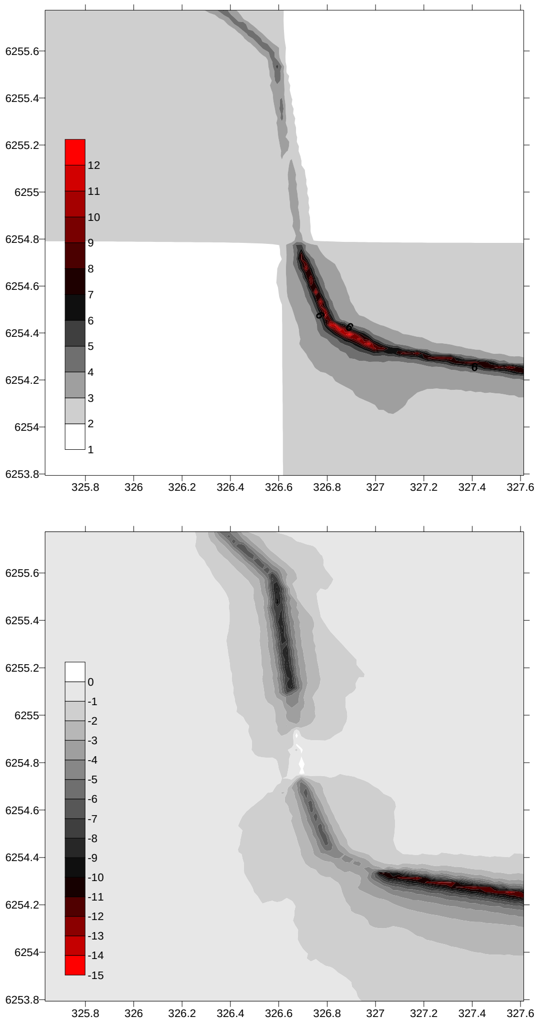

Figure 6. Top- mortality (deaths per km^2 per day x10^4) for PM_{10} emissions from, and within the vicinity of Victoria Rd. Bottom- percentage difference in mortality resulting from the implementation of the BTM ITS scenario.

4. Conclusions

In this paper we have introduced and demonstrated components of an Intelligent Transport System demonstration tool. The tool consists of systems for modelling transport networks, vehicular emissions, urban-scale and road-scale pollutant dispersion and air pollution-related mortality.

One of the models developed specifically for the ITS-GHG demonstration tool is the Lagrangian Wall Model. The model provides the capability of modelling near-road pollutant impacts for scalar and reactive pollutants within an urban environment. These components of the ITS–GHG tool will continue to be refined. In particular, data for the TransCAD modelling will be updated to be representative of post 2000 conditions; when considering highly reactive air pollutants (such as 1,3 butadiene), TAPM–CTM, an enhanced version of TAPM with comprehensive chemical transformation modelling, will be used to generate urban-scale pollutant fields; the operation of LWM will be further streamlined; consideration will be given to high-resolution modelling of population movement to complement the LWM concentration predictions.

References

ABS 2004. Media release on deaths in Australia. http://www.abs.gov.au/Ausstats/abs@.nsf/5f1e01afb32859f9ca25697500217f48/374ea85206d5de3aca256f6a0074f99a!OpenDocument

Brunekreef, B. and Holgate S.T., 2002. Air pollution and health. Lancet, 360: 1233–1242.

Carnovale F., Tilly K., Stuart A., Carvalho C., Summers M. & Eriksen P., 1996. Metropolitan air quality study: Air emissions inventory, New South Wales Environment Protection Authority, Bankstown, NSW.

Hurley, P. J., 2002. The Air Pollution Model (TAPM) Version 2: user manual. Aspendale: CSIRO Atmospheric Research. (CSIRO Atmospheric Research internal paper; 25). 38 p.

Lilley W., and Cope M., 2005. Development of a high resolution chemically reactive near-field dispersion model for assessing the impact of motor vehicle emissions. Part 1: model description and validation. Proceedings of 17th International Clean Air Conference, Hobart, Australia.

NEPC, 2002. Impact statement for $PM_{2.5}$ variation. http://www.ephc.gov.au/pdf/Air_Variation_PM25/draft_variation_is.pdf

Smith N. and Kilsby D. 2003. Transport Network Modelling, Technical Paper 2 of the Modelling Responses of Urban Freight Patterns to Greenhouse Gas Abatement Measures Study, BTRE: Canberra.

Zito, R. and Taylor M., 2003. Urban Road Freight Greenhouse Gas Emissions Modelling. Technical Paper 3 of the Modelling Responses of Urban Freight Patterns to Greenhouse Gas Abatement Measures Study, BTRE: Canberra, Australia.