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SOUTH EAST QUEENSLAND MOTOR VEHICLE FLEET AIR EMISSIONS INVENTORY 2000, 2005, 2011

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Summary

An inventory and model of emissions of air pollutants from the motor vehicle fleet has been developed for the South East Queensland region. The model consists of a travel demand model, a vehicle emissions factor database and a fleet emissions model. Travel demand over the region is modelled using the EMME/2 model and the local (South East Queensland region) road network, vehicle fleet, traffic operations and demographic data. The emissions factor database is largely based on Australian data of vehicle emissions. Model results of low and high travel demand in 2005 and 2011 were combined with a predicted increased uptake of tighter emissions limits (ADR79/00, ADR79/01, ADR80/00, ADR80/01) by the motor vehicle fleet. The results indicate that reductions of vehicle emissions of CO and NOX will be counter-balanced by a significant travel-demand for a high travel-demand scenario, while reductions of the fleet's PM10 and VOC emissions can be achieved for both low and high travel demand scenarios.

Keywords: travel demand modelling, vehicle emission factors, regulated pollutants, fleet emissions.

1. Introduction

Recent decisions of the Commonwealth Government on the regulation of emissions from vehicles in Australia will have a profound impact on the future emissions of both passenger cars and light- and heavy-duty vehicles. The "Measures for a Better Environment" contains an accelerated timetable for the adoption of new vehicle emissions and fuel standards, including

- staged introduction of Euro2 and Euro3 standards for light-duty petrol, LPG and CNG/LNG vehicles;
- staged introduction of Euro2, Euro3 and Euro4 standards for diesel and medium/heavy-duty LPG and CNG/LPG vehicles.

This paper presents a model of vehicle fleet emissions and inventories of emissions of regulated air pollutants, including carbon monoxide (CO), oxides of nitrogen (NOX), fine particles (PM10) and non-methane volatile organic compounds (VOC), from the South East Queensland motor vehicle fleet for the years 2000, 2005 and 2011.

The fleet emissions model and inventories have been developed as part of the air emissions inventory initiative of the Queensland Environmental Protection Agency and Brisbane City Council and are largely based on Australian vehicle emissions data and local (South East Queensland) data on fuel quality, fleet composition and travel demand. The principal reason for focusing heavily on Australian data of vehicle emissions is that there are very significant differences between Australia and other countries in fuel quality, engine technologies, fleet composition and emission standards.

2. Modelling of Fleet Emissions

2.1. Database of Vehicle Emission Factors

Australia now has a comprehensive, locally generated data on the emissions performance of in-service vehicles for regulated pollutants. A database of emission factors for 86 vehicle categories representing relevant combinations of vehicle type, fuel type and vehicle vintage (ie. compliance date or manufacturing year) and the composition of the local vehicle fleet, were derived from measurements of Australian in-service vehicles.

In typical on-road operations, emission rates of each pollutant are dependent on a number of factors, the most significant being vehicle age, vehicle type and mass, fuel used and driving conditions. Driving conditions also strongly influence emissions, for instance stop-start driving in congested traffic generates quite different emissions patterns to free-flowing or highway travel. A number of secondary factors can also affect on-road emissions such as cold start, ambient temperatures, road gradient and use of air-conditioning.

Australian measurements include the testing programmes of some 770 diesel vehicles and 670 petrol-fuelled passenger cars and light-duty vehicles. The programmes, which include data from simulated "real-world" conditions, are

- The Composite Urban Emissions Driving Cycle (CUEDC) for diesel-fuelled light- and heavy-duty vehicles (NEPC 1999-2001);
- The DT80, a short (approximately 5 minute) test for diesel-fuelled light-and heavy-duty vehicles; designed to give a rapid assessment of vehicle performance (NEPC 1999-2001).
- The Australian Urban Driving Cycle (AUC) for a limited number of petrol-fuelled passenger cars, that generated information on driving and cold-start emissions obtained in Melbourne, Sydney and Brisbane (DoTRS 2001).

In addition to these "real-world" drive cycle measurements, test data of the ADR27 and AD37 cycles are available from studies conducted by the Federal Bureau of Road Safety/Environment Australia (1996-1997) and DoTRS(2001).

These test programmes together with research programmes (eg. Duffy et al., 1999) have generated a considerable body of data on emissions from Australian in-service vehicles of all regulated pollutants as well as carbon dioxide. Table 1 lists the number of vehicles in each vehicle category, which were tested in these programmes. Petrol- and LPG-fuelled Passenger cars (PC) and light-duty vehicles (LCV) have been categorised according to their emissions standards, ie. Australian Design Rules (ADR) for their manufacturing year. The ADR37/00 category was split between 1986-1988 for two-way catalyst/one-point injection vehicles and 1989-1997 three-way catalyst/multi-point injection vehicles. Diesel-fuelled LCV, medium-duty commercial vehicles (MCV) and heavy-duty commercial vehicles (HCV) have been categories by mass and manufacturing year.

Table 1: Summary of vehicle categories and number of tested vehicles (NV) tested in Australian emissions testing programmes.

PC, LCV Petrol, LPG	NV	LCV, MCV, HCV Diesel (1980-99)	NV
Pre-ADR <1976	10	PC, 4WD	81
ADR27 1976-1985	206	LCV <3.5t	150
ADR37/00-O 1986-88	185	MCV3.5-12t	199
ADR37/00-T 1989-97	241	HCV >12t	160
ADR37/01 1997-03	30	Art. Trucks	140
ADR36/00 1986-03	6	Bus	47

CUEDC replicates Australian driving patterns in a range of traffic conditions, from congested inner-city roads to urban freeways. The DT80 data have been found to have excellent correlation with the overall CUEDC cycle. CUEDC drive cycle also contains cold starts. Drive cycles used for ADR27 and ADR37 testing of passenger cars and light-duty vehicles tend to underestimate real-world emissions, as they have lower acceleration rates and average speeds than the AUC.

The approach used in deriving vehicle emissions factors is based on the derivation of a total driving cycle emission factors, or "base emission factors" for each vehicle category, ie. a factor that is independent of traffic conditions or travel speed. These base emission factors consist of exhaust running emission factors (grams per kilometre of travel), and cold-start and hot-start emission factors (grams per start).

Table 2: Derived total-drive-cycle exhaust running emission factors

ADR	CO [g/km]	HC [g/km]	NO_x [g/km]
Petrol PC - PRE ADR27	32.4	2.77	1.54
Petrol PC - ADR27	27.3	2.07	1.82
Petrol PC - ADR37/00 O	13.0	0.82	1.20
Petrol PC - ADR37/00 T	4.9	0.38	1.05
Petrol PC - ADR37/01	1.0	0.11	0.38
Petrol PC - ADR36/00	6.2	0.55	1.79
LPG PC - PRE-ADR27	30.6	1.54	1.32
LPG PC - ADR27	29.3	1.47	1.32
LPG PC - ADR37/00 O	16.1	1.15	2.22
LPG PC - ADR37/00 T	6.9	0.29	1.63
LPG PC - ADR37/01	1.0	0.11	0.38
Petrol LCV < 2.7t PRE ADR27	32.4	2.77	1.54
Petrol LCV < 2.7t ADR27	32.4	2.75	1.82
Petrol LCV < 2.7t ADR37/00 O	15.7	1.03	1.20
Petrol LCV < 2.7t ADR37/00 T	10.8	0.98	1.20
Petrol LCV < 2.7t ADR37/01	1.6	0.18	0.62
Petrol LCV 2.7-3.5t ADR36/00	15.0	1.21	1.79
LPG LCV < 2.7t PRE-ADR27	30.6	1.54	1.32
LPG LCV < 2.7t ADR27	30.6	1.54	1.32
LPG LCV < 2.7t ADR37/00 O	19.4	1.42	2.22
LPG LCV < 2.7t ADR37/00 T	15.9	0.65	2.20
LPG LCV < 2.7t ADR37/01	10.1	0.32	0.60

In addition to the total cycle emissions, the real-world conditions drive-cycles provide emission rates for each individual road mode (highway, arterial, congested, minor) including vehicle starts. These data are used in the derivation of speed-based emission factors for a range of traffic speeds and cold- and hot-start emission factors from the base factors. Base emission factors were broken down into a hot-running, hot-start and cold-start component. This approach was adopted as traffic speed based emission factors and cold-/hot-start factors are directly applicable to fleet emissions modelling using a strategic travel demand model.

Base emissions factors were categorised by fuel types, ADR category and age (compliance date) and for light- and heavy-duty diesel also by test mass resulting in 85 vehicle categories. Table 2 presents the derived total drive-cycle emission factors for running exhaust emissions for selected vehicle categories.

Emission factors for evaporative emissions are largely based on SHED tests, including recent Ethanol/petrol-blend studies (Apace Research 2001), comprising in total of approximately 400 tests. These data provide estimates of diurnal and hot soak evaporative emissions only. Running-loss and resting-loss evaporative emissions estimates were developed using methods adopted from US EPA's MOBILE6 emissions model.

Running-loss evaporative emissions depend strongly on the driving cycle (Pierson et al. (1999)). Hot soak evaporative losses occur over one hour after the engine is shut down. Diurnal evaporative losses take place as the fuel tank expels air and petrol vapour as it heats up during the day. These emissions are dependent on ambient temperature and the period of vehicle non-operation.

Emission factors for vehicles manufactured to comply with Euro3 and Euro4 standards have been calculated by multiplying the emission factors developed for the current (2000) vehicles by the ratio of emission limit for the new standard to the emission limit for the current standard.

2.2. Vehicle Fleet and Travel Data

Data of vehicle fleet composition and travel data were obtained from a range of sources, including the Survey of Motor Vehicle Use (ABS 2000), South East Queensland Household Travel Survey (SEQHTS) (QT 1992), Brisbane City Council's Brisbane Strategic transport Model (BSTM) (SKM 2000), traffic count data and motor vehicle registrations.

Year 2000 demographic data for each travel zone include population, number of households, average number of persons, workers and dependents per household, average number of cars per household, employment (by 13 separate industry classifications) and enrolments (for primary, secondary, tertiary and TAFE students).

SEQHTS 1992 data of 10 separate trip purposes, including 3 commercial vehicle related purposes, are presented in Table 3. The comparatively large number of trip purposes for passenger car and motorcycle trips reflect the significant contribution that these vehicle classes make to the total transport task within the region (ie. ~70% of all trips). Furthermore, the disaggregation of passenger car and motorcycle travel into seven separate trip purposes acknowledges the fundamental differences in trip length, vehicle occupancy, mode share and trip start times associated with each purpose.

Table 3: Observed Trip lengths (min) (SEQHTS 1992).

Vehicle Class & Purpose	SC[1]	BRI[2]	GC[3]	WS[4]
PCs & Motorcycles				
home based work	11.6	17.8	13.8	13.6
home based shopping	8.0	7.5	7.7	13.6
home based education	8.5	9.1	8.9	11.2
home based recreation	7.9	9.4	9.4	8.8
home based other	7.9	7.7	8.4	11.8
non-home based	8.1	9.3	9.7	11.2
visitors	19.4	17.8	21.3	-
Light Commercials	10.0	12.8	11.6	12.2
Medium Commercials	12.3	15.7	14.3	15.0
Articulated Vehicles	22.7	29.1	26.3	27.7

[1] SC=Sunshine Coast, [2] BRI=greater Brisbane, [3] GC=Gold Coast, [4] WS=Western Shires.

More recent data (ABS 2000) of travel mode-split for each travel purpose and vehicle occupancy were obtained leading to the apportioning of trips amongst the available modes (eg. walk, cycle, car, train, bus).

For the purpose of year 2005 and 2011 scenario modelling, changes in the vehicle fleet were estimated and high/low estimates of future population growth, trends in VKT per capita, public transport mode share and car pooling derived from observed data for other regions around the country.

The most significant changes in the motor vehicle fleet, which were estimated for 2005 and 2011, are:

- In 2005, the decrease of the proportion of pre-1986 manufactured petrol-fuelled passenger fleet cars to less than 13% and the increase of the proportion of post-1998 manufactured cars to 40%;
- In 2011, the decrease of the proportion of the pre-1986 manufactured petrol-fuelled cars to less than 5% and the increase of the proportion of post-1998 manufactured petrol-fuelled cars to almost 62% with the proportion of post-2003 manufactured cars of 31%.
- In 2005 and 2011, the uptake of post-2003 manufactured diesel-fuelled light- and medium commercial vehicles of approximately 20% and 40%, respectively.

The population of South East Queensland is expected to increase by 18-28% between 2000 and 2011;similarly the number of jobs within the region is expected to increase by 29-38% between 2000 and 2011; the change in private vehicle mode share is expected to range from –6% and up to +5% between 2000 and 2011; the change in average vehicle occupancy is expected to range from +6% down to –5%; the change in average trip length is expected to range from +7% up to +9%.

The region's road network data includes information on the signed speed limit and the number of traffic lanes during the morning and evening peak hours (ie. under clearway conditions). The base year (2000) road network was updated for all future year analyses (ie. 2005 and 2011) to include committed road improvement works.

2.3. Vehicle Fleet Emissions Model

2.3.1. *Travel Demand*

Estimates of vehicle kilometres of travel (*VKT*) on the study area road network were generated with the aid of a travel demand model. The EMME/2 based model implements the traditional four step transportation modelling approach, namely trip generation, trip distribution, mode split and trip assignment and includes the trip generation and commercial vehicle components of the more recently developed BSTM.

The model takes account of the relative attractiveness of zones (as measured by their trip productions and attractions), their separation (in terms of travel time) and the observed distribution of trip lengths. The calibration process lead to a close agreement of average trip lengths with the observed year 1992/93 statistics.

In total, 40 EMME/2 model runs have been performed: four sub-regions (greater Brisbane, Gold Coast, Sunshine Coast and Western Shires), weekday and weekend and five time zones (morning off-peak, morning peak, afternoon-off-peak, afternoon peak, evening/night off peak). The resulting estimates of link volumes for vehicle types were split by fuel type and vehicle vintage, in accordance with the observed proportions of *VKT* within each category and multiplied by the corresponding link length to calculate *VKT*. The first 505 seconds of travel were defined as the start of a vehicle travel. The resulting number of vehicle starts per link were split into 47% cold starts and 53% hot starts.

An overlay analysis of the *VKT* and vehicle start data on a 1km by 1km resolution grid was performed for generating the database of gridded and temporally resolved *VKT* and number of vehicle starts. A similar overlay analysis of road grade of the road network was performed resulting in 1km resolution data of road grade.

2.3.2. *Fleet Emissions*

The fleet emissions model estimates exhaust emissions from running and starting vehicles, non-exhaust (evaporative) running losses and evaporative emissions (hot soak, resting and diurnal) while the vehicles are stationary. Fleet emissions are calculated for each grid cell and hour of day. The fleet emissions of a particular pollutant, *i*, from all vehicle categories, *k*, is given by

$$T_i = \sum_{k=1}^{ncat} Exh_{ik} + Ev_{ik} \qquad , \qquad (1)$$

where *ncat* is the number of vehicle categories, *Exh* and *Ev* are the exhaust and evaporative emissions.

Exhaust emissions for a vehicle category, *k*, are dependent on travel-speed, *VKT* and the number of starts. Hourly exhaust emissions for the five time zones are calculated, using Eq. (2), as the sum of running exhaust and cold/hot-start exhaust emissions.

$$\begin{aligned} Exh_{ik} &= VKT_k \cdot EF_{ik}^{Exh} * (1 + CF_{ik}^{GR} + CF_{ik}^{SA}) + \\ &\quad MSt_k \cdot EF_{ik}^{ExhSt} \quad , \qquad (2) \end{aligned}$$

where *VKT* are the vehicle kilometres of travel (km), EF^{Exh} is the travel-speed dependent exhaust emission factor (gram/km), *MSt* is the number of cold/hot-starts at the particular hour and EF^{ExhSt} is the exhaust cold/hot-start emission factor (gram/start). The modifying factors are the road grade correction (CF^{Gr}) and seasonal air conditioning correction (CF^{SA}) factors.

Evaporative emissions for a vehicle category, *k*, are dependent on travel speed, *VKT* and the number of stationary vehicles. Evaporative emissions are calculated using Eq. (3) for each hour of the five time zones as the sum of running evaporative emissions and evaporative emissions of stationary vehicles. The number of stationary vehicles is approximated by the number of cold starts (or "events").

$$\begin{aligned} Ev_{ik} &= VKT_k * EF_{ik}^{EvRun} + NSt_k \cdot EF_{ik}^{HS} + \\ &\quad OSt_k \cdot \left(EF_{ik}^{Rest} + EF_{ik}^{DU} \right) \quad , (3) \end{aligned}$$

where EF^{EvRun} is the travel-speed dependent emissions factor (gram/km) for running evaporative emissions, Ev^{Rest} is the hourly emissions factor (gram/event) for resting-loss emissions, EF^{DU} is the hourly emission factor (gram/event) for diurnal losses, EF^{HS} is the emission factor for hot soak emissions (gram/event), *NSt* is the number of cold starts at the particular hour, *OSt* is the number of cold starts during the preceding evening and morning travel-peak hours.

Hourly resting and diurnal evaporative losses are calculated for six hours following the morning and afternoon post travel-peak periods. This assumes that all vehicles travelling during the travel-peak periods remain stationary during the following six hours. For example, the number of stationary vehicles between hours 9 am and 3 pm is assumed to be equal the number of cold starts between 7am and 8am.

2.3.3. *Fleet Average Emission Factors*

Fleet average emissions factors arising from all vehicle categories are dependent on their *VKT* fractions, number of cold/hot-starts and number of stationary vehicles per total *VKT*. For a given location and hour of day the fleet emission factor (g/km) for species, *i*, is given by Eq. (4).

$$E_i = T_i \Big/ \sum_{k=1}^{ncat} VKT_k \qquad . \qquad (4)$$

3. Results

3.1. Vehicle Kilometres of Travel

The year 2000 *VKT* is based on an estimated population in the SEQR of 2,321,330 persons with 1,043,181 persons being employed. The annual *VKT* is estimated at 21.4 billion kilometres. Figure 1. shows the spatial pattern of estimated *VKT*. Passenger cars generate the majority of *VKT* (ie.79%), with light commercial the next most significant class (ie. 14%). Motorcycles, medium commercial, articulated vehicles and buses account for 6% of annual *VKT*. Petrol-fuelled vehicles are estimated to account for the majority of *VKT* (ie. 88%), with diesel vehicles the next most significant category (ie. 10%). LPG and CNG fuelled vehicles are predicted to account for 2% of annual *VKT*.

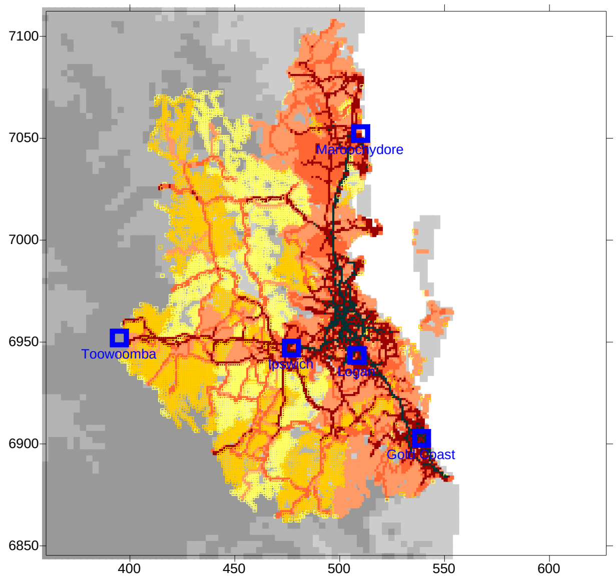

Figure 1: Domain of travel demand model and emissions inventory for South East Queensland with the sub-regions of greater Brisbane (incl. Ipswich and Logan), Gold Coast, Sunshine Coast (Maroochydore) and Western Shires. Shown is the spatial distribution (1km resolution) of the predicted annual *VKT* for the baseline year 2000. *VKT* values are represented by yellow to dark red colours for a range from less than 5,000 km (intra-zonal travel) in regional zones to 10,000,000 km (inter-zonal travel) on major highways and arterial roads.

The travel-demand modelling forecasts for 2000 to 2011 are:

- A 10-17% increase in *VKT* between 2000 and 2005 compared to an 8-12% increase in population; the higher growth in *VKT* is underpinned by the continued growth in trip-lengths associated with ongoing urban-sprawl;
- A 30-50% increase in *VKT* between 2000 and 2011 compared to an 18-28% increase in population;
- Regional *VKT* increases at over twice the rate of the population, due mainly to the continued trends towards higher private mode share, lower vehicle occupancies and longer trip lengths;
- Small variations in the *VKT* and fuel-type proportions of passenger cars, light and medium commercial vehicles, articulated trucks, buses and motorcycles compared to 2000.

3.2. Fleet Average Emission Factors

Table 4 lists the estimated fleet average emissions factors (during travel peak hours 7-8am) for CO, NOX and VOC for two road categories characterised by average travel speed. The data indicate a significant increase of NOX emissions with traffic speed and significant decrease of CO emissions and VOC emissions from lowest to highest traffic speed.

Table 4: Predicted fleet-average emission factors[1] [gram/km] of regulated pollutants for selected roads in greater Brisbane.

Road Type	AvSp[4]	CO	VOCx[5]	VOC[6]	PM10	NOX
FW[2]	108	13.2	0.85	1.86	0.15	2.83
FW[2]	85	14.8	1.00	1.64	0.14	2.35
FW[2]	65	15.0	1.05	1.94	0.09	1.95
AR[3]	58	16.9	1.36	3.00	0.10	2.32
AR[3]	33	23.4	1.90	3.16	0.08	2.32

[1] Eq. (4), without road grade correction and seasonal air conditioning correction factors, [2] freeway/highway, [3] arterial road, [4] average travel speed [km/h], [5] exhaust emissions only, [6] exhaust and evaporative emissions.

3.3. Annual Emissions: Year 2000

Table 5 presents the estimated annual emissions of regulated pollutants, greenhouse gases and selected air toxic species for the baseline year 2000 in the model domain. The results (including road grade and seasonal air conditioning corrections) are:

- CO emissions of 417,300 tonnes, with 96% from petrol-fuelled vehicles and passenger cars contributing to 84% of the annual emissions.
- PM10 emissions of 2,200 tonnes, with 75% from diesel-fuelled vehicles compared to the annual VKT contribution of 9% of that vehicle category. 51% of the PM10 emissions arise from light commercial vehicles, medium commercial vehicles and trucks and only 27% by passenger cars.
- NOX emissions of 60,500 tonnes, with 60% from petrol-fuelled vehicles compared to the annual VKT contribution of 89% from this vehicle category. The rest (39%) arises almost entirely from diesel-fuelled vehicles compared to their annual *VKT* contribution of 10%.
- VOC emissions of 79,600 tonnes arise to 98% from petrol-fuelled cars. The VOC emissions from petrol-fuelled vehicles consist to 69% of emissions from evaporative losses.

The prediction of a high percentage of evaporative emissions is in qualitative agreement with US studies (Pierson et al., 1999), which report that evaporative emissions from petrol-fuelled vehicles constitute most of the total motor vehicle fleet's VOC emissions.

Table 5: Estimated annual emissions [x1000 tonnes] for year 2000.

	PM10	NOX	VOC	CO
No GR and SA[1]	2.0	50.0	78.0	372.0
With GR and SA[1]	2.2	60.5	79.6	417.3

[1] road grade (GR) and seasonal air conditioning correction (SA).

3.4. Emission Trends: 2000-2011

The major factors determining the 2000-2011 trend of motor vehicle fleet emissions are (i) the change in travel demand (ie. *VKT*), (ii) the change in vehicle vintage distribution of the fleet associated with the increased uptake of tighter emissions limits regulated by ADR79/00, ADR79/01, ADR80/00 and ADR80/01. The predicted emissions trends for high and low travel-demand scenarios compared to the baseline year 2000 for the regulated pollutants are:

- PM10: small changes in 2005 and large decrease –23% ("low") and –11% ("high") in 2011;
- NOX: small increase (less than 4%) in 2005 and small changes between –8% ("low") and 6% ("high") in 2011;
- VOC: decrease in 2005 between –22% ("low") to –14% ("high") and between –41% ("low") and –24% ("high") in 2011;
- CO: decrease between 8% ("low") and lass than 1% ("high") in 2005 and changes between –13% ("low") and +13% ("high") in 2011.

4. Conclusions

The inventory was developed with the focus on using up-to-date data on travel demand in South East Queensland and Australian data on operating conditions of the motor vehicle fleet.

The *VKT* estimation stage of this project has drawn on a range of disparate sources. Up-to-date local information is required in particular on personal travel behaviour through a new round of household travel surveys and commercial vehicle travel, specifically average trip rates and lengths by vehicle type.

The emissions factor database is largely based on Australian data of vehicle emissions. The NEPC projects, and associated studies by Environment Australia and the Australian Greenhouse Office, have transformed the availability of reliable Australian emissions data on diesel vehicles. Nevertheless, a number of gaps remain in the knowledge base including exploration of emissions at higher speeds than those in the CUEDC cycle and cold-start emissions. Evaporative emissions form a large proportion of total VOC emissions. The evaporative emissions factors are a major source of uncertainty.

Model results of low and high travel demand in 2005 and 2011 were combined with a predicted increased uptake of tighter emissions limits (ADR79/00, ADR79/01, ADR80/00, ADR80/01) by the motor vehicle fleet. The results indicate that reductions of vehicle emissions of CO and NOX will be counter-balanced by increased travel-demand, while reductions of the fleet's PM10 and VOC emissions can be achieved for both low and high travel demand scenarios.

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