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# Fuel Consumption and Emissions Models for Traffic Engineering and Transport Planning Applications: Some New Results

**Michael A.P. Taylor**
Professor of Civil Engineering and Director, Transport Systems Centre
University of South Australia

**Troy M. Young**
Research Engineer, Institute of Transportation Studies
University of California at Davis

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# FUEL CONSUMPTION AND EMISSIONS MODELS FOR TRAFFIC ENGINEERING AND TRANSPORT PLANNING APPLICATIONS: SOME NEW RESULTS

**Michael A P Taylor**
Professor of Civil Engineering and Director, Transport Systems Centre
University of South Australia

**Troy M Young**
Research Engineer, Institute of Transportation Studies
University of California at Davis, USA

## SUMMARY

Some new fuel and emissions models for different vehicle types have been developed, based on the Biggs-Akçelik hierarchy of fuel consumption models. The models extend the set of available models to include 4-cylinder and 6-cylinder EFI passengers cars running on unleaded petrol. Models for individual vehicle types may be combined to yield models for the performance of a traffic stream. The models allow detailed investigation of the effects of traffic congestion on fuel consumption and emissions. The models may then be incorporated into transport network performance studies, as tools for use in the prediction of environmental and energy impacts of road transport projects, from the individual intersection to the metropolitan level. The role of the traffic stream models in environmental impact analysis is indicated, through the development of the IMPAECT supermodel.

The energy and emissions models yielded by this research are for modern unleaded petrol vehicles. They thus enlarge the set of known models of passenger vehicle performance, for use in traffic engineering and transport planning applications. The models in the paper are the first comprehensive results of the project. Further work has still to be reported, and this will further enlarge the set of available models.

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Mike Taylor is Professor of Civil Engineering and Director of the Transport Systems Centre at the University of South Australia. His principal research and teaching interests lie in traffic systems engineering, transport planning and urban planning, although he has diverse interests in civil engineering and related disciplines, including engineering management, systems engineering and operations research, computer modelling, information technology and computer science, and policy and decision-making support systems. He has strong interests in Intelligent Transport Systems (ITS), especially with regard to the application of information technology to traffic and transport engineering problems, including (a) Geographic Information Systems (GIS) through the imperative need to tie traffic, transport, road accident, land use and environmental impact databases together through their shared spatial attributes, (b) Knowledge-Based Systems (KBS) through the need to establish comprehensive, safe and robust control strategies for traffic control and management, and (c) Global Positioning Systems (GPS) and related location and tracking technologies for the need to develop real-time vehicle tracking and navigation systems for dynamic route guidance and scheduling systems .

Professor Taylor has worked in industry, with the Country Roads Board of Victoria, and most recently as an expert consultant to the transport industry at large. His previous position was Reader in Transport Engineering at Monash University (1984-91). He spent eight years with the CSIRO Division of Building Research, and two years with the Organisation for Economic Cooperation and Development in Paris.

Troy Young has been a research engineer at the Institute of Transportation Studies of the University of California at Davis since January 1995. He was previously part of the Transport Systems Centre at the University of South Australia where he did both his undergraduate and graduate studies. Troy is currently completing his PhD thesis (Energy Use and Exhaust Emissions Modelling for Road Traffic) in which he developed fuel consumption and exhaust emission models for modern passenger vehicles in Australia.

Troy has been involved in several projects at ITS-Davis, but most of his effort has been committed to two major projects. The first aims to prepare a protocol for developing driving cycles representative of specific facility types and levels of service. The project will measure 'modal' activity under different levels of service on freeways and arterial roadways in California. The results of this research will be applied to improved vehicle emissions modelling. This research work is a two year effort funded by the California Department of Transportation. The second major project aims to identify and prioritise environmentally beneficial ITS technologies. Data is being collected from ITS deployments and field operational tests in the USA, and a modelling framework is being established and applied to evaluate the environmental impacts of a range of transportation technologies.

## INTRODUCTION

1. This paper presents the results of a research project on the pollutant emissions and fuel consumption characteristics of mixed traffic streams under different levels of congestion. The project involved extensive testing of a number of modern passenger cars, both on-road and in the laboratory, to determine their fuel consumption and emissions performance. The findings reported in the paper update and extend previous research by providing information on the fuel and emissions performance of EFI vehicles using unleaded petrol, and the presentation of this information in forms suitable for use in traffic engineering and transport planning. This information has important applications in environmental impact analysis in both traffic engineering and transport planning studies.

2. Models for three types of Australian passenger cars have been developed, using the Biggs-Akçelik hierarchy of fuel consumption models (Biggs and Akçelik, 1986). Models for individual vehicle types may be combined to yield models for the performance of a traffic stream. In particular, the models allow detailed investigation of the effects of traffic congestion on fuel consumption and emissions. The models may then be incorporated into transport network performance studies, as tools for use in the prediction of environmental and energy impacts of road transport projects, from the micro level (e.g. an individual intersection) to the macro level (e.g. a metropolitan arterial road network). For instance, the models have been included in the IMPAECT (Impact Model for the Prediction and Assessment of the Environmental Consequences of Traffic) super-model for environmental impact analysis of transport planning decisions. IMPAECT comprises a traffic network model, the family of emissions and fuel consumption models, a pollution dispersion model, and a land use impact model.

## THE IMPAECT SUPERMODEL

3. The basic scheme of the IMPAECT supermodel system is as follows (see Figure 1). A traffic network model is used to produce (by simulation or forecasting) the levels of traffic flow and travel conditions on a study area network, under the given traffic management scheme. Models of vehicle fuel consumption and emissions under the modelled traffic conditions are then used to estimate the traffic system fuel usage and the levels and spatial distribution of pollution generation. This information, coupled with data on the meteorological conditions, may then be used as input to a pollution dispersion model, which estimates the spread of the pollution over the study area, so providing the modelled levels and spatial distribution of the pollution. The land use impact model superimposes the pollution levels on the land uses and populations in the study area to determine the likely sites and extent of environmental problems resulting from the traffic system.

4. The necessary information to be supplied to, or generated by, IMPAECT comprises the total flows and travel conditions (travel time, delays, queuing, congestion) on links in the network, the volume and composition of the traffic stream (in terms of vehicle and/or fuel type). Emission and fuel consumption rates may then be estimated by aggregating the contributions of the component traffic streams. The network is then treated as a set of line sources of each pollutant. The emissions from these sources may then be spread over the study region using the dispersion model, and the concentrations of pollution at different sites examined.

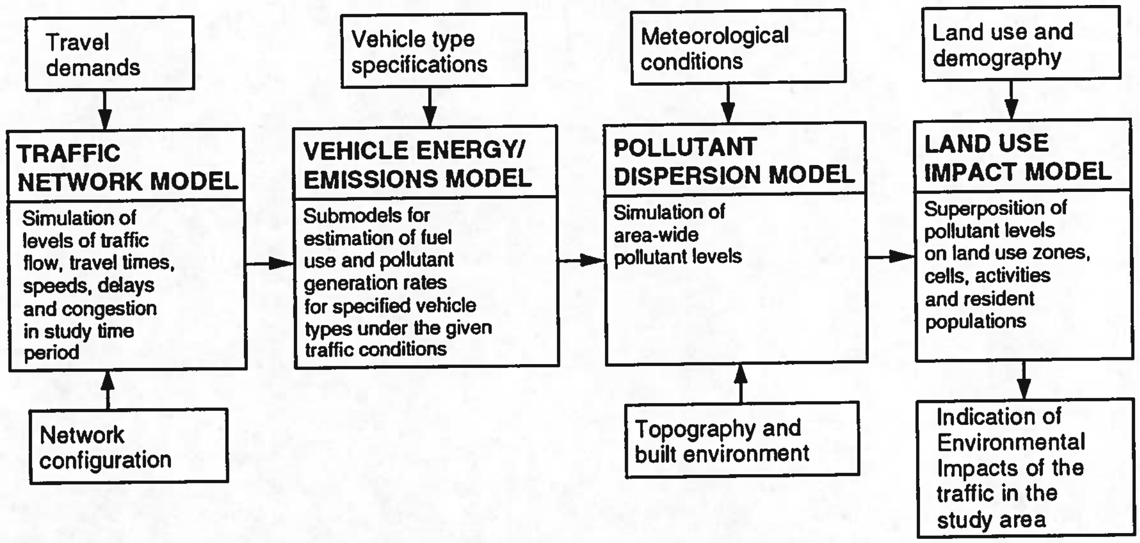


**Figure 1: Schematic modelling structure of the IMPAECT supermodel**

5. IMPAECT provides the capability of including environmental planning decisions in the transport planning framework so that potential environmental problems resulting from transport infrastructure development or modification can be identified in the planning stages. Solutions to those problems can then be devised and tested in conjunction with the development of the transport plans, rather than as remedial treatments or curtailment of the project at a later stage. A full description of the IMPAECT system is available in Woolley and Young (1994).

## THE BIGGS-AKÇELIK FAMILY OF MODELS

6. A family of four models for fuel consumption and emissions modelling was proposed by Biggs and Akçelik (1986). This family provides specific models to cover a wide range of traffic circumstances, from the performance of an individual vehicle driven in traffic to a model for a total door-to-door trip. The Biggs-Akçelik models are:

(a) an *instantaneous model*, that indicates the rate of fuel usage or pollutant emission of an individual vehicle continuously over time;

(b) an *elemental model*, that relates fuel use or pollutant emission to traffic variables such as deceleration, acceleration, idling and cruising, etc. over a short road distance (e.g. the approach to an intersection);

(c) a *running speed model*, that gives emissions or fuel consumption for vehicles travelling over an extended length of road (e.g. representing a network link); and

(d) an *average speed model*, that indicates level of emissions or fuel consumption over an entire journey.

7. The instantaneous model is the basic (and most detailed) model. The other models are aggregations of this model, and require less and less information but are also increasingly less accurate. The elemental model is the next most detailed model, and is suitable for intersection or road section analysis where the focus is on an entity in the road system (such as the intersection or a traffic control device) rather than the individual vehicles negotiating that entity. The running speed model is suitable for application in strategic networks, for it can be used at the network link level. Regional 'sketch' planning studies which do not include a formal (link-node) description of the transport network can make good use of the average speed model. The models were originally defined by Biggs and Akçelik (1986). Descriptions of their interrelationships and applications in

transport planning and traffic engineering are given in Taylor (1995) and Taylor and Young (1996). A description of the instantaneous and elemental models is useful, for this defines the particular parameters that need to be determined for different vehicles and different fuels and emissions. The running speed and journey speed models are basically aggregations of the more detailed models. Interested readers can find descriptions of them in the references cited above.

## INSTANTANEOUS MODEL

8. This model is suitable for the detailed assessment of traffic management schemes for individual intersections or sections of road. It may be used for comparisons of the behaviour of individual vehicles under different traffic conditions. The variables in the model include instantaneous values such as speed $v(t)$ and acceleration $a(t)$ at time $t$. The instantaneous model gives the rate of emission/consumption (E/C) of fuel or emission type $X$, including components for:

(a) the fuel used or emissions generated in maintaining engine operation, estimated by the idle rate ($\alpha$);

(b) the work done by the vehicle engine to move the vehicle, and

(c) the product of energy and acceleration during periods of positive acceleration.

The energy consumed in moving the vehicle is further divided into drag, inertial and grade components. Part (c) allows for the inefficient use of fuel during periods of hard acceleration. The model is:

$$\frac{dE(X)}{dt} = \alpha + \beta_1 R_T v + \left[\frac{\beta_2 M a^2 v}{1000}\right]_{a>0} \qquad R_T > 0$$

$$\frac{dE(X)}{dt} = \alpha \qquad R_T \leq 0 \tag{1}$$

where $v$ is the speed (ms$^{-1}$); $a$ is the instantaneous acceleration in ms$^{-2}$; $R_T$ is the total tractive force required to drive the vehicle, which is the sum of the drag, inertial and grade forces; $M$ is the vehicle mass in kg; $\alpha$ is the idling fuel consumption or pollutant emission rate; $\beta_1$ is an engine efficiency parameter (mL or g per kJ), relating E/C to energy provided by the engine; and $\beta_2$ is an engine efficiency parameter (mL or g per (kJ.ms$^{-2}$)) relating E/C during positive acceleration to the product of inertia energy, and acceleration. $R_T$ is given by:

$$R_T = b_1 + b_2 v^2 + \frac{Ma}{1000} + g\left(\frac{M}{1000}\right)\left(\frac{G}{100}\right) \tag{2}$$

where $g$ is the gravitational acceleration in ms$^{-2}$; $G$ is the percentage gradient (negative downhill); $b_1$ is a drag force parameter relating *mainly* to rolling resistance; and $b_2$ is a drag force parameter relating *mainly* to aerodynamic resistance. Both of the drag force parameters also reflect some component of internal engine drag. The model has been found to estimate the fuel consumption of individual vehicles to within five per cent. Recent dynamometer tests suggest that its accuracy for emissions modelling is to within ten per cent. The five parameters $\alpha$, $\beta_1$, $\beta_2$, $b_1$ and $b_2$ are specific to a particular vehicle, and the idling rate and energy efficiency parameters ($\alpha$, $\beta_1$ and $\beta_2$) depend on the type of fuel or emission as well.

## ELEMENTAL MODEL

9. The most suitable model for estimating fuel consumption and emissions of traffic at an intersection or on a road section is the elemental model. This model considers the trajectories of vehicles traversing the section. It can be used to estimate the additional emissions or fuel usage incurred compared to the case of an equivalent road section without intersection or traffic control

device. This is done by considering the speed-time profile of vehicles using the section, and describing this profile in terms of the following five elements (hence the name of the model):

(1) cruising, the vehicle enters the road section at a constant speed;
(2) deceleration, the vehicle has to brake to join the back of a queue;
(3) idling, the vehicle waits in the queue with engine idling;
(4) acceleration, the vehicle accelerates as the queue moves off; and
(5) cruising, the vehicle resumes cruising as it leaves the section.

The elemental model thus considers the incremental effects of delays, queuing and numbers of stops and starts due to the traffic controls, for a defined section of road. The required input data include cruise speed ($v_c$), number of stops, stopped time ($t_i$), road section distance ($x_s$) and average gradient of the road over the section prior to, and after, the intersection.

10. The total volume of fuel consumed or pollutant emitted per vehicle over the section ($E_s(X)$) is composed of the consumption or emission over the cruise-deceleration-idle-acceleration-cruise cycle. The model is constructed by summing the fuel consumption or pollutant emission in each element of this cycle:

$$E_s(X) = f_{c1}(x_{s1} - x_d) + F_d + \alpha t_i + F_a + f_{c2}(x_{s2} - x_a) \qquad (3)$$

where $f_{c1}$, and $f_{c2}$ are cruise E/C rates per unit distance for the initial and final cruise speeds $v_{c1}$ and $v_{c2}$; $x_{s1}$, and $x_{s2}$ are section distances on approach and departure, respectively; $x_d$, and $x_a$ are deceleration and acceleration distances, respectively; $F_d$, and $F_a$ are the total deceleration and acceleration E/C, respectively; $\alpha$ is the idle E/C rate; and $t_i$ is the idle or stopped time (sec).

11. The elemental model provides estimates of fuel consumption within ten per cent of observed values. Indeed, given that it is computationally easier to apply than the instantaneous model, its performance is commensurate with its more detailed cousin. The elemental model is recommended for traffic engineering applications, where the focus is generally on the fuel and emissions effects of an element of the road system (e.g. an intersection) rather than on those of individual vehicles traversing that element.

## TRAFFIC STREAM COMPOSITION

12. Changing fleet composition and the contributions of different vehicle types and trip classes to fuel usage and pollution are important influences in the estimation of pollutant emissions from road traffic. The differences in energy and environmental performance between automobiles using alternative fuels such as unleaded petrol, leaded petrol, liquid petroleum gas, diesel fuel or electricity is one such issue. Trip class might include different categories of travellers, e.g. through traffic and local traffic, private, commercial and business travel, etc. If $q(e)$ is the total vehicle volume on link $e$ then:

$$q(e) = \sum_k q_k(e) \qquad (4)$$

where $q_k(e)$ is the volume of trip class $k$ vehicles on $e$. If $p_{km}$ is the proportion of type $m$ vehicles in trip class $k$ then the flow $q_m(e)$ of type $m$ vehicles is given by equation (5):

$$q_m(e) = \sum_k p_{km} q_e(k) \qquad (5)$$

It therefore follows that if $E_m(X)$ is the mean rate (per unit length) of emission (consumption) of pollutant (fuel) $X$ by a type $m$ vehicle then $TE_e(X)$, the total rate of emission (consumption) of $X$ on link $e$ is given by:

$$TE_e(X) = \sum_{km} E_m(X) p_{km} q_k(e) \tag{6}$$

In the common situation where trip class data are not readily available or cannot be accommodated in the computations, then an equivalent formulation can be used:

$$TE_e(X) = q(e) \sum_{m} p_m E_m(X) \tag{7}$$

where $p_m$ is the proportion of type $m$ vehicles in the traffic stream.

13. Thus if models can be established to predict $E_m(X)$ for a range of traffic conditions, total pollution loads and fuel consumption can be estimated. These models will have the ability to suggest differences in energy and environmental impacts for changes in levels of traffic flow and congestion and for changes in vehicle fleet composition. The basic form of such models is known, but only limited data (for a restricted number of vehicle types) has been available. This research reported in this paper extends the database of available vehicle types, as described later in this chapter. Segmentation of vehicles into size and/or fuel type classes in the manner suggested provides the means to derive reasonably accurate estimates of fuel consumption and emissions in transport network models.

14. A substantial amount of research of the characteristics and dynamics of the Australian vehicle fleet was carried out as part of this project. It is not possible to adequately summarise all the findings here, but some of the most useful information is presented. More complete information is given in Taylor *et al* (1995). If vehicles of type $m$ are defined by their vehicle type *and* fuel type, then $p_m$ would represent the proportion of vehicles for a given fuel type/vehicle type combination. Ideally, one wishes to know the proportion of type $m$ vehicles in trip class $k$ ($p_{km}$) but where the breakdown by trip class is unknown, $p_m$ could be used at least as a starting point.

15. Figure 2 shows the composition of the Australian and South Australian vehicle fleets in terms of fuel type/vehicle type combinations, at the time of the 1991 ABS Motor Vehicle Census. Clearly, the large majority of both the Australian and South Australian vehicle fleets is made up of leaded petrol fuelled passenger vehicles (52.4 per cent and 57.8 per cent, respectively). However, this situation is changing. In 1994, sales (by volume) in Australia of unleaded petrol exceeded those of leaded petrol for the first time. This does not directly reflect the distribution of unleaded/leaded petrol vehicles within the vehicle fleet, though, because newer vehicles (namely, unleaded petrol vehicles) travel a greater proportion of the total fleet VKT.

## FUEL AND EMISSION DATA FOR MODERN PASSENGER VEHICLES

16. The most significant recent shortcoming of the Biggs-Akçelik family of models and its application was the absence of model parameters for modern, unleaded fuelled, electronic fuel injected (EFI) vehicles. This research helps to overcome this difficulty.

### DATA COLLECTION METHODOLOGY

17. The Transport Systems Centre (TSC) at the University of South Australia purchased two modern passenger vehicles to be used to collect on-road and laboratory data that could be used to determine the required parameters. The first vehicle was a 1991 Toyota Camry sedan. This vehicle was powered by a two-litre, four-cylinder electronic fuel injected (EFI) engine and had a four-speed automatic transmission. The Camry was subsequently replaced with a 1993 Ford Falcon wagon, powered by a four-litre, six-cylinder EFI engine with a four-speed automatic transmission. The vehicles were fitted with ARRB's Fuel Consumption and Travel Time Data Acquisition

System (FCTTDAS) which was used to collect on-road second-by-second speed profile and fuel consumption data for both urban driving conditions and under controlled testing conditions.

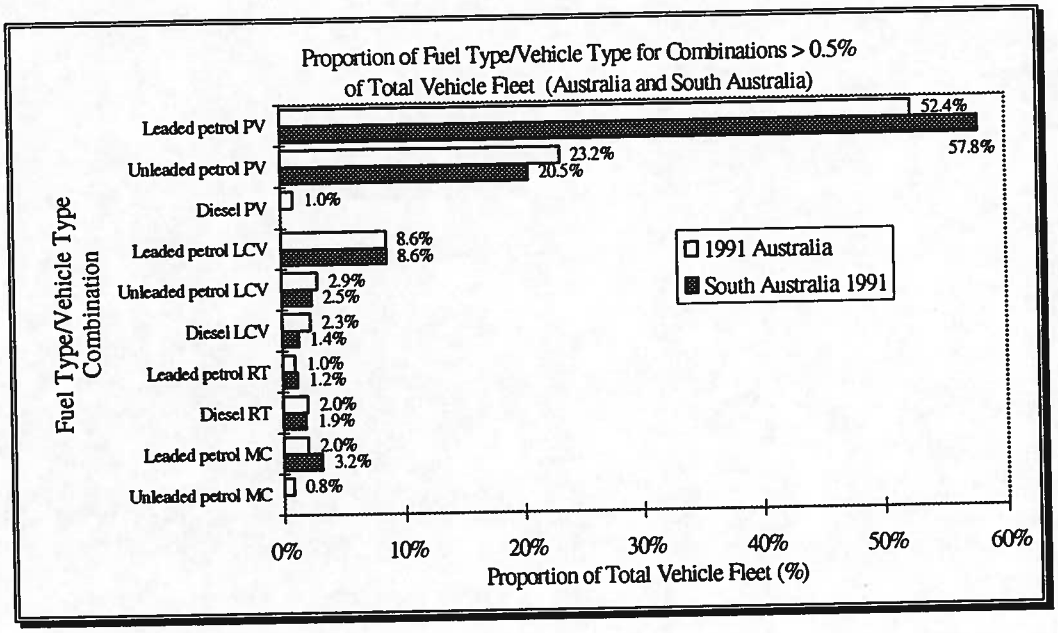


**Figure 2: Fuel type/vehicle type combinations (Australian and South Australian vehicle fleets; 1991)**

## On-road controlled tests

18. The simplest 'controlled' tests were the idle tests to determine the idle fuel consumption rate of the engine. It is important to accurately determine the idle fuel consumption rate, as the fuel used to keep the engine idling is an important component of the fuel used under all conditions. Idle fuel consumption rate varies with the temperature of the engine; higher fuel consumption rates occur when the engine is cold. The idle tests were performed for a range of operating temperatures and hence the resulting data set had a large range. Each idle test was carried out over 300 seconds and the fuel rate averaged over that period. In order to make sense of the wide range of fuel consumption rates that were being measured, the engine temperature condition for each test was recorded as cold, cool, warm or hot. It is assumed that for the majority of urban driving the engine temperature is in the warm range; hence most of the tests were done for this condition. The vehicle parameter, $\alpha$ is described as the idle fuel consumption rate of a warm engine.

19. The instrumented vehicles were first used to collect speed profile and fuel consumption data under controlled driving conditions. This testing was carried out in an environment free from the influences of other traffic and where road geometry was constant (flat, straight, rural road). The 'controlled' driving tests included constant speed (or cruise) tests for the determination of parameters for the cruise fuel consumption model. The test vehicles were driven at cruise speeds of 10 km/h to 110 km/h in increments of 10 km/h. Another stage of the 'controlled' testing consisted of acceleration phases for a range of speeds and acceleration rates. Acceleration phases from rest up to speeds of 110 km/h were carried out for acceleration rates of 2 km/h/s to 6 km/h/s in increments of 1 km/h/s. The data from this testing and the acceleration fuel consumption models developed from it are presented below. Data was also collected for deceleration phases for a wide range of speeds and deceleration rates. The decelerations were performed from greater than 100

km/h to rest at deceleration rates ranging from 0.5 km/h/s to 12 km/h/s. The results of this testing are given later in the paper.

**Dynamometer tests**

20. The Toyota Camry was also used to collect fuel consumption and exhaust emissions data on a chassis dynamometer operated by the Environment Protection Authority (EPA) of Victoria. A series of controlled tests was performed to obtain modal emissions data for acceleration, deceleration and cruise phases. The emission testing involved operating the vehicle on the standard urban driving cycle (the Federal Test Procedure cycle) through the cold start, stabilised and hot start phases and then the 'cold' start and stabilised phases were repeated with the engine hot. The main purposes of this stage of the testing was twofold: (a) to check that the emissions from this vehicle were comparable with similar vehicles previously tested; and (b) to check that the results were repeatable, by comparing the first hot start with the second 'cold' start and comparing the two stabilised phases. The result from the second stabilised phase was within 4.2 per cent of the first result for HC, 1.0 per cent for CO, 2.9 per cent for $NO_x$, 2.7 per cent for $CO_2$ and 7.0 per cent for fuel use. The data processor also analysed the emission mass for each of eighty modes throughout the cycle. These results are not presented in this paper due to space limitations.

21. After completion of the standard tests, a series of controlled modal tests were performed. These modal tests included acceleration phases from rest to 100 km/h, decelerations from 100 km/h to rest and cruise (steady-speed) tests at speeds from 10 km/h to 100 km/h in 10 km/h increments. The acceleration and deceleration phases were performed at a constant rate of acceleration and covered a range of acceleration/deceleration rates from 2 km/h/s to 6 km/h/s. Due to the vehicle performance and limitations of the dynamometer (not having large diameter rollers), it was not possible to sustain an acceleration rate greater than 6 km/h/s over the full range of speeds. The idle emission rate was determined from the idle modes within the urban driving cycle. During the controlled modal tests, exhaust emission concentration and mass, exhaust volume, air-fuel ratio, fuel mass, oxygen content and dynamometer speed were recorded on a second-by-second basis. The emissions and fuel consumption data were adjusted to account for the respective lags in the exhaust system and the analysers, using previously determined lag times.

## MODEL DEVELOPMENT FOR TOYOTA CAMRY

22. This section describes the development of on-road fuel consumption models and carbon monoxide exhaust emission models for the Toyota Camry instrumented vehicle.

**On-road fuel consumption models**

23. The on-road fuel consumption modelling development was based on the data collected during the on-road controlled testing described above. On-road testing with the Toyota Camry provided estimates of the idling fuel consumption rate and a cruise fuel consumption model. The idling fuel consumption rate was determined as $\alpha$ = 0.294 mL/s. The cruise fuel consumption model is fitted to the form given in equation (8).

$$f'_{c,t} = \alpha + c_1 v + c_2 v^3 \tag{8}$$

where $f'_{c,t}$ is the constant-speed cruise fuel consumption, in mL/s; $\alpha$ is the idle fuel consumption rate, in mL/s; $c_1$ is the drag fuel consumption component in mL/m, mainly due to rolling resistance; $c_2$ is the drag fuel consumption component in $(mL/m)/(m/s)^2$ mainly due to aerodynamic resistance; and $v$ is the instantaneous speed, in m/s. The coefficients $c_1$ and $c_2$ are obtained by regression of $f'_{c,t}$ with speed $v$ and $v^3$; with the constant term set to α. Figure 3 shows the regression curve fitted to the data obtained from the cruise tests for the Toyota Camry. This curve is described by:

$$f'_{c,t} = 0.294 + 0.0311v + 0.00004v^3 \quad (9)$$

The coefficient of determination ($R^2$) for this curve was found to be 0.980. The other curve shown in Figure 3 is for the ARRB 'default' car described in (Bowyer *et al*, 1985). The ARRB 'default' car was representative of a group of vehicles running on leaded petrol. Table I shows the values determined for $c_1$ and $c_2$ for the Toyota Camry, the Ford Falcon and the ARRB 'default' car.

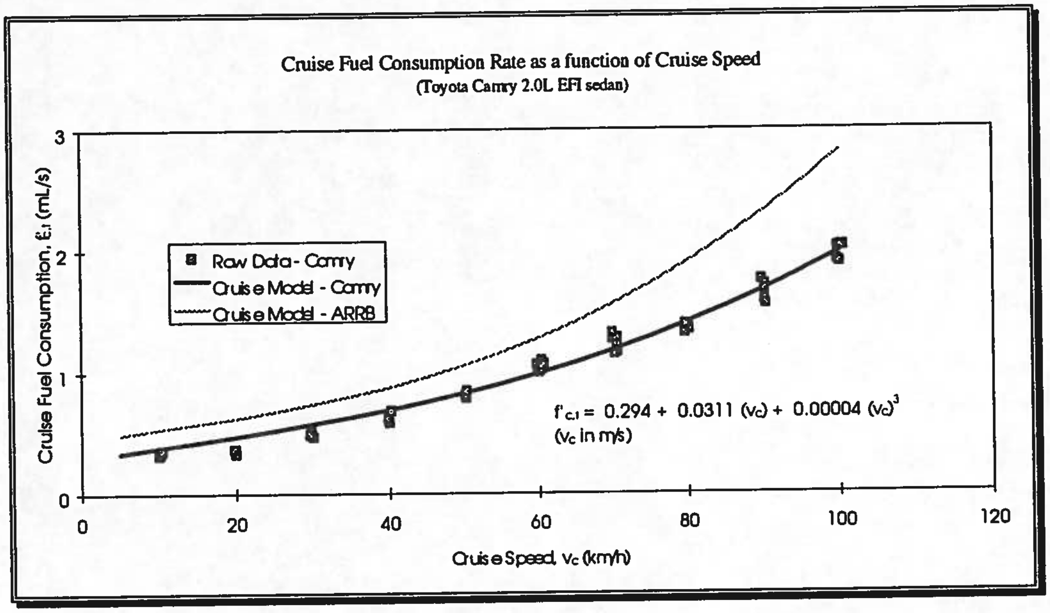


**Figure 3: Cruise fuel consumption rate as a function of cruise speed (Toyota Camry; controlled on-road tests)**

**TABLE I**
**CRUISE FUEL CONSUMPTION MODEL PARAMETERS FOR THE TOYOTA CAMRY, FORD FALCON AND ARRB DEFAULT CAR**

| Parameter | Toyota Camry | Ford Falcon | ARRB Default Car |
|---|---|---|---|
| $c_1$ (mL/m) | 0.031 | 0.049 | 0.030 |
| $c_2$ (mL/m)/(m/s) | 3.84E-05 | 4.94E-05 | 7.20E-05 |

**Acceleration phase models**

24. The controlled testing to obtain data for acceleration phases resulted in large data sets. For example, the data set for the Toyota Camry contained more than 3400 data points (see Figure 4). Data collected during the acceleration tests were used to develop acceleration fuel consumption functions of the form given in equation (10):

$$F_a = Av_f + Bv_f^2 \quad (10)$$

where $F_a$ is the acceleration fuel consumption, in mL (for accelerations from rest to $v_f$); and $v_f$ is the final speed of the acceleration phase, in m/s. The regression curve ($R^2 = 0.985$) for the Toyota Camry acceleration phase data is shown in Figure 4 and is given by:

$$F_a = 0.409v_f + 0.118v_f^2 \tag{11}$$

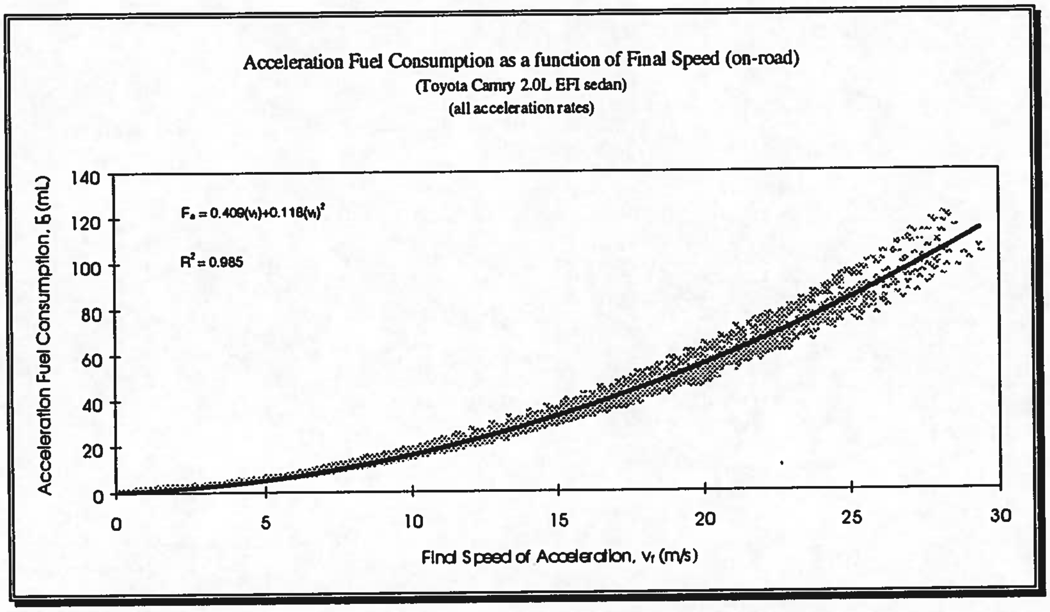


**Figure 4: Acceleration fuel consumption as a function of final speed of acceleration and acceleration rate (Toyota Camry, controlled on-road data)**

25. The width of the band of data points is due to the range of acceleration rates included in the testing. Given the observed differences resulting from the range of acceleration rates, an on-road acceleration fuel consumption function was developed for all acceleration rates and separate functions were developed for five sub-sets of data; each set with a range of acceleration rates spanning only 1 km/h/s (e.g. 1.51 km/h/s - 2.5 km/h/s; 2.51 km/h/s - 3.5 km/h/s; ... 5.51 km/h/s - 6.5 km/h/s). The acceleration rates here are average rates for each acceleration phase; that is, the total change in speed since the start of the acceleration over the time of the phase ($\Delta v/\Delta t$), as opposed to instantaneous acceleration rates. Table II indicates the coefficients ($A$ and $B$, in equation (11)) of the functions and the coefficients of determination, $R^2$ for each range of acceleration rates.

**TABLE II**
**MODEL COEFFICIENTS FOR TOYOTA CAMRY ON-ROAD ACCELERATION FUEL CONSUMPTION FUNCTIONS**

| Acceleration rate (km/h/s) | Coefficient of $v_f$, A | Coefficient of $v_f^2$, B | Coefficient of determination, $R^2$ |
|---|---|---|---|
| 1.51-2.5 | 0.4736 | 0.1302 | 0.999 |
| 2.51-3.5 | 0.4317 | 0.1175 | 0.999 |
| 3.51-4.5 | 0.3933 | 0.1129 | 0.999 |
| 4.51-5.5 | 0.4613 | 0.1029 | 0.999 |
| 5.51-6.5 | 0.5189 | 0.1004 | 0.999 |
| all rates | 0.4089 | 0.1182 | 0.994 |

**Deceleration phase models**

26. Figure 5 shows the data collected with the Toyota Camry for controlled decelerations to rest. These data were also divided into subsets, defined by specific ranges of deceleration rates. The range of deceleration rates is much greater than the range of acceleration rates, since decelerations depend less on vehicle performance than do accelerations. The subsets were defined in intervals of 1 km/h/s. Table III presents the coefficients and $R^2$ values for the regression curves fitted to the data. The form of the deceleration functions is the same as for accelerations (see equation (10)), except that $F_a$ is replaced by $F_d$ (the deceleration fuel consumption, in mL) and $v_f$ is replaced by $v_i$ (the initial speed of the deceleration phase, in m/s).

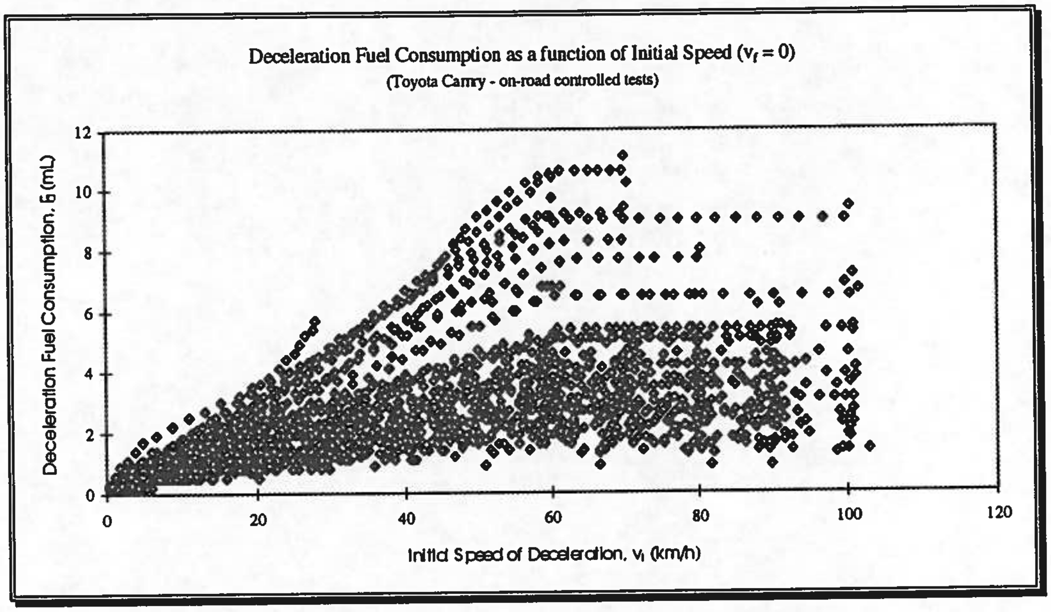


**Figure 5: Deceleration fuel consumption as a function of initial speed of deceleration and deceleration rate (Toyota Camry, controlled on-road data)**

**TABLE III**
**MODEL COEFFICIENTS FOR TOYOTA CAMRY ON-ROAD DECELERATION FUEL CONSUMPTION FUNCTIONS**

| Deceleration rate (km/h/s) | Coefficient of $v_i$, A | Coefficient of $v_i^2$, B | Coefficient of determination, $R^2$ |
|---|---|---|---|
| 0.5-1.5 | 0.2281 | -0.0013 | 0.985 |
| 1.5-2.5 | 0.1735 | -0.0006 | 0.977 |
| 2.5-3.5 | 0.1162 | -0.0006 | 0.975 |
| 3.5-4.5 | 0.0848 | -0.0004 | 0.988 |
| 4.5-5.5 | 0.0701 | -0.0003 | 0.987 |
| 5.5-6.5 | 0.0611 | -0.0003 | 0.993 |
| 6.5-7.5 | 0.0513 | -0.0003 | 0.990 |
| 7.5-8.5 | 0.0441 | -0.0002 | 0.994 |
| 8.5-9.5 | 0.0437 | -0.0003 | 0.989 |
| 9.5-10.5 | 0.0374 | -0.0002 | 0.995 |
| 10.5-12.5 | 0.0374 | -0.0002 | 0.997 |

## DETERMINATION OF VEHICLE PARAMETERS

27. The energy-related instantaneous model and the four-mode elemental model have in common a set of vehicle parameters, namely $\alpha$, $b_1$, $b_2$, $\beta_1$, $\beta_2$ and $M$. Bowyer *et al.* (1985) sets out a procedure for deriving these parameters from on-road data.

28. The vehicle mass, $M$ is determined simply by weighing the vehicle while it was loaded in the same way as for data collection. This vehicle mass includes the mass of the vehicle, the mass of fuel, the mass of the driver and the mass of any passengers.

29. The idle fuel consumption rate, $\alpha$ was determined in the manner described previously. The energy efficiency parameter, $\beta_1$ is related to the vehicle drag force parameters, $b_1$ and $b_2$ by the drag fuel consumption components, $c_1$ and $c_2$, described in equation (8). The relationships are as follows:

$$\beta_1 = \frac{c_1}{b_1} = \frac{c_2}{b_2} \qquad (12)$$

The drag fuel consumption components, $c_1$ and $c_2$ were determined as described previously and are shown for the Toyota Camry in Table I. Hence, it was only necessary to find $\beta_1$ and $\beta_2$ since $b_1$ and $b_2$ can then be found from equation (12). To determine $\beta_1$ and $\beta_2$ it was necessary to collect instantaneous (typically second by second) speed, grade and fuel consumption values over at least 1000 seconds of driving. The range of speeds and accelerations are required to be typical of those experienced in normal driving conditions and the wind speed should be low. Each instrumented vehicle was used to collect almost 1500 seconds of data along a section of Main North Road; a major arterial road in Adelaide. Road grade information was extracted from the data collected with the ARRB Road Geometry Data Acquisition System (RGDAS) in 1992. The complete parameter sets for the Toyota Camry, Ford Falcon and the ARRB default car are shown in Table IV.

## APPLICATION OF INSTANTANEOUS MODEL

30. The instantaneous model was applied with the parameters for the Ford Falcon to the speed profile shown in Figure 6, with the appropriate road grade data. This data set contains 1247 records of second-by-second data (i.e. almost 21 minutes). The trip error, ER, was calculated to be 2.11 per cent and the average error on a second-by-second basis was 2.92 per cent. The trip error is defined as the sum of the errors for each data record, divided by the total measured fuel consumption. Figure 6 also shows a plot of cumulative predicted and measured fuel consumption.

**TABLE IV**
**FUEL PARAMETERS FOR TOYOTA CAMRY, FORD FALCON AND ARRB DEFAULT CAR**

| Parameter | Toyota Camry | Ford Falcon | ARRB Default Car |
|---|---|---|---|
| $\alpha$ | 0.294 | 0.500 | 0.444 |
| $\beta_1$ | 0.068 | 0.094 | 0.090 |
| $\beta_2$ | 0.041 | 0.031 | 0.030 |
| $b_1$ | 0.455 | 0.517 | 0.333 |
| $b_2$ | 0.00056 | 0.00160 | 0.0008 |
| $M$ | 1250 | 1850 | 1200 |

## CARBON MONOXIDE EXHAUST EMISSION MODELS

31. The data collected for the Toyota Camry on the EPA chassis dynamometer was used to develop exhaust CO emissions models, for cruise, acceleration and deceleration phases. The average idle CO emission rate was found to be 0.007 g/s.

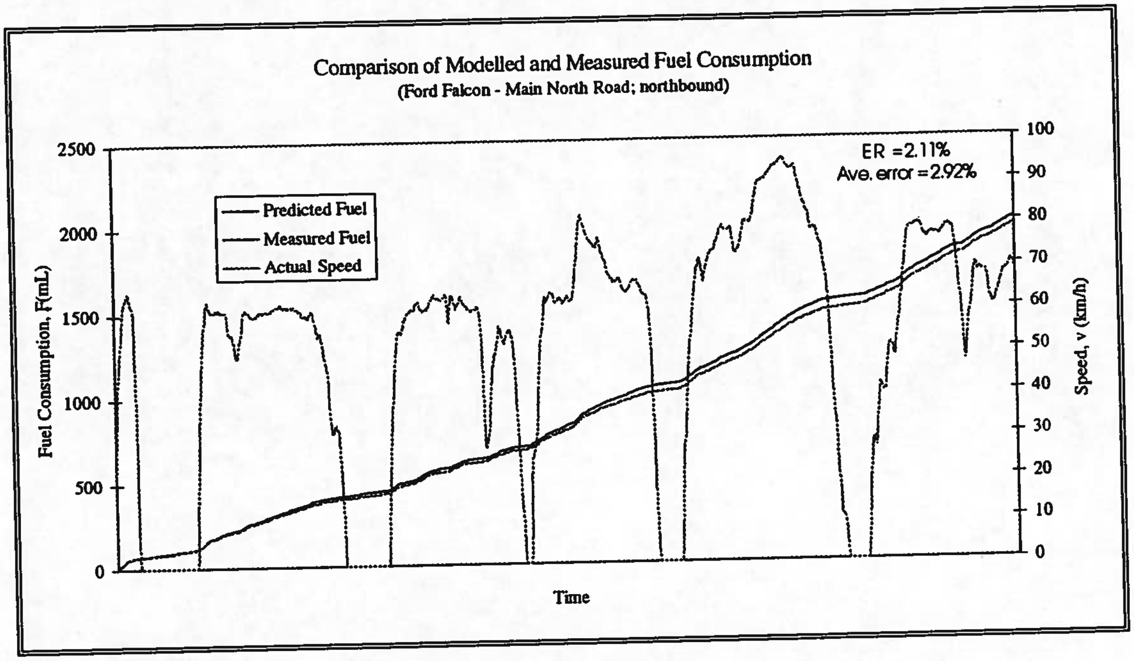


**Figure 6: Performance of instantaneous model for the Ford Falcon**

### CRUISE (STEADY-SPEED) MODELS

32. Steady-speed emissions data were collected for hydrocarbons, carbon monoxide, nitric oxides and carbon dioxide. A plot of the carbon monoxide emission rates as a function of cruise speed is shown in Figure 7. Clearly the relationship between emission rate and cruise speed for carbon monoxide emissions is not as obvious as the relationship between fuel rate and cruise speed. This observation could be explained by the influences of factors other than the cruise speed. One such factor is the temperature of the engine and/or the catalytic converter. Catalytic converters operate more efficiently as they warm up. The main purpose of a catalytic converter is to convert CO emissions to $CO_2$. Figure 7 shows a significant drop in the CO emission rate between cruise speeds of 30 km/h (8.3 m/s) and 40 km/h (11.1 m/s). The CO emission rate for cruise speeds greater than 40 km/h is relatively constant between 0.0007 g/s and 0.0014 g/s. Obviously the data set is best modelled in two parts; a curve between 0 and 40 km/h (11.1 m/s) and a separate curve or straight line segment for speeds greater than 40 km/h. A suitable composite curve is:

$$E(CO)_c = 0.007 + 0.0007v + 0.0009v^2 - 0.00009v^3 \qquad [0 \le v \le 11.2 \text{ m/s}] \qquad (13)$$

and

$$E(CO)_c = 0.0022 - 0.0002v + 0.000005v^2 \qquad [v > 11.2 \text{ m/s}] \qquad (14)$$

The cubic and quadratic curves intersect at a speed of v = 11.2 m/s and hence equation (13) should be applied for speeds v ≤ 11.2 m/s and equation (14) should be used beyond this. The two curve segments are shown superimposed on the data points in Figure 7.

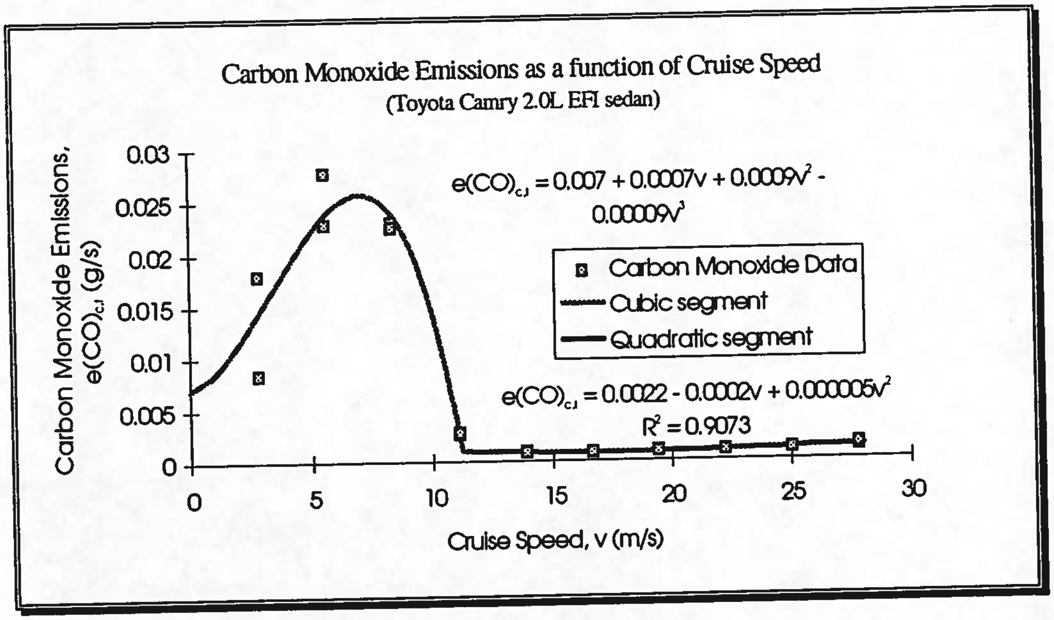


**Figure 7: Cruise carbon monoxide emission rate as a function of cruise speed (Toyota Camry; controlled dynamometer test)**

## ACCELERATION PHASE MODELS

34. Most of the variation in the acceleration CO emissions for a given final speed was found to be explained by differing acceleration rates. A model was developed to describe the complete data set in terms of the final speed of each acceleration, regardless of acceleration rate, and other models were developed for each of four subsets based on average acceleration rate (acceleration rates from 1.51 to 2.5 km/h/s, 2.51 to 3.5 km/h/s, 3.51 to 4.5 km/h/s and 4.51 to 5.5 km/h/s). The model form that best described the acceleration CO emissions data was:

$$E(CO)_a = Ae^{Bv_f} \qquad (15)$$

where $E(CO)_a$ is the acceleration CO emissions in grams; $v_f$ is the acceleration final speed in km/h; and $A$ and $B$ are regression coefficients, shown in Table V.

**TABLE V**
**MODEL COEFFICIENTS FOR ACCELERATION CO EMISSION FUNCTIONS FOR THE TOYOTA CAMRY**

| Acceleration rate (km/h/s) | Constant term, A | Coefficient of $v_f$, B | Correlation coefficient, r |
|---|---|---|---|
| 1.51-2.5 | 0.0211 | 0.0562 | 0.988 |
| 2.51-3.5 | 0.0112 | 0.0628 | 0.962 |
| 3.51-4.5 | 0.0126 | 0.0712 | 0.985 |
| 4.51-5.5 | 0.0754 | 0.0552 | 0.982 |
| all rates | 0.0181 | 0.0651 | 0.857 |

## DECELERATION PHASE MODELS

35. The deceleration data were divided into five subsets, for deceleration rates from -1.51 to -2.5 km/h/s, -2.51 to -3.5 km/h/s, -3.51 to -4.5 km/h/s, -4.51 to -5.5 km/h/s and -5.51 to -6.5

km/h/s. Models of the form shown in equation (10) (with $F_a$ replaced by $E(CO)_d$, the deceleration CO emissions, in g) and $v_f$ replaced by $v_i$ (in km/h)) were found to best describe the variation in deceleration emissions for each subset. The linear coefficient of $v_i$ was only significant at the 95 per cent level for the subset of deceleration rates from -3.51 to -4.5 km/h/s. The regression coefficients and model correlation coefficients for each data subset are shown in Table VI.

**TABLE VI**
**MODEL COEFFICIENTS FOR DECELERATION CO EMISSION FUNCTIONS FOR THE TOYOTA CAMRY**

| Deceleration rate (km/h/s) | Coefficient of $v_i$, A | Coefficient of $v_i^2$, B | Correlation coefficient, r |
|---|---|---|---|
| 1.51-2.5 | ns | 0.00013 | 0.935 |
| 2.51-3.5 | ns | 0.00012 | 0.961 |
| 3.51-4.5 | -0.00421 | 0.00036 | 0.992 |
| 4.51-5.5 | ns | 0.00040 | 0.982 |
| 5.51-6.5 | ns | 0.00046 | 0.994 |

ns = not significant

## CONCLUSIONS

36. This paper has provided some new data and models for fuel consumption and emissions for EFI passenger cars currently used in Australia. Models for individual vehicle types may be combined to yield models for the performance of a traffic stream. In particular, the models allow detailed investigation of the effects of traffic congestion on fuel consumption and emissions. They may be incorporated into transport network performance studies, as tools for use in the prediction of environmental and energy impacts of road transport projects, from the micro level (e.g. an individual intersection) to the macro level (e.g. a metropolitan arterial road network). The role of the traffic stream models in environmental impact analysis was indicated through the development of the IMPAECT supermodel. The energy and emissions models yielded by this research enlarge the set of known models of passenger vehicle performance, for use in traffic engineering and transport planning applications. Further work from the overall research project has still to be reported, and this will further enlarge the set of available models.

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