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DEVELOPING A SET OF FUEL CONSUMPTION AND EMISSIONS MODELS FOR USE IN TRAFFIC NETWORK MODELLING

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This paper introduces 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 vehicles, both on-road and in the laboratory, to determine their fuel consumption and emissions characteristics under different traffic conditions. A set of models for different vehicle types were then assembled, based on the hierarchical family of models for fuel consumption presented by Biggs and Akcelik (1986), which was also capable of describing vehicle emission rates. The model family consists of models at four levels, from an 'instantaneous' model for individual vehicles driven in traffic, through an 'elemental' model suitable for studies of intersection behaviour, a 'link' model suitable for transport network analysis, and a 'journey' model suitable for land use planning applications. The models for individual vehicle types may be combined to yield models for the performance of a traffic stream. These models may then be incorporated into transport network analysis performance, as tools for use in the prediction of environmental and energy impacts of road transport projects. One such integration of the models into a super-model (IMPAECT) for environmental impact analysis of transport planning decisions is described. The focus is on the development and application of the energy and emissions models, which are made up of three sub-models: (1) traffic stream composition sub-models, to determine the emissions or fuel consumption of a traffic stream as an aggregate of the vehicles in that stream, (2) congestion functions, to relate travel conditions (delays, queuing and speed-time trajectories) to traffic flows on particular types of roads, and (3) sub-models of vehicle energy and emissions performance under different traffic conditions.

THE IMPAECT SUPERMODEL

IMPAECT, the Impact Model for the Prediction and Assessment of the Environmental Consequences of Traffic, comprises a traffic network model (capable of producing a number of alternative travel patterns in response to differing transport policies), a family of emissions and fuel consumption models, a pollution dispersion model, and a land use impact model. The principal reason behind the development of IMPAECT is to provide the capability of including

environmental planning decisions in the transport planning framework in such a way 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. An inherent part of the rationale behind IMPAECT is the idea that the manifestation of environmental impacts as they affect sensitive land uses is the desired model output for the planner and decision maker. Amounts of pollution emitted from the transport system or its individual components is not enough, the levels of immission of those pollutants by sensitive land uses (e.g. residential areas) and the effects of those pollutants on those land uses must be examined - see Wigan (1976), Brown and Patterson (1990) and Taylor (1995).

IMPAECT consists of a connected set of four sub-models that are linked through a common data structure and make extensive use of interactive graphics displays and Geographic Information Systems (GIS), thus improving their utility as decision support systems for transport and land use planners. The sub-models include a transport network model, a vehicle energy and emissions (air and noise) model, a pollutant dispersion model and a land use environmental impact model, as shown in Figure 1. A full description of the IMPAECT system is available in Woolley and Young (1994).

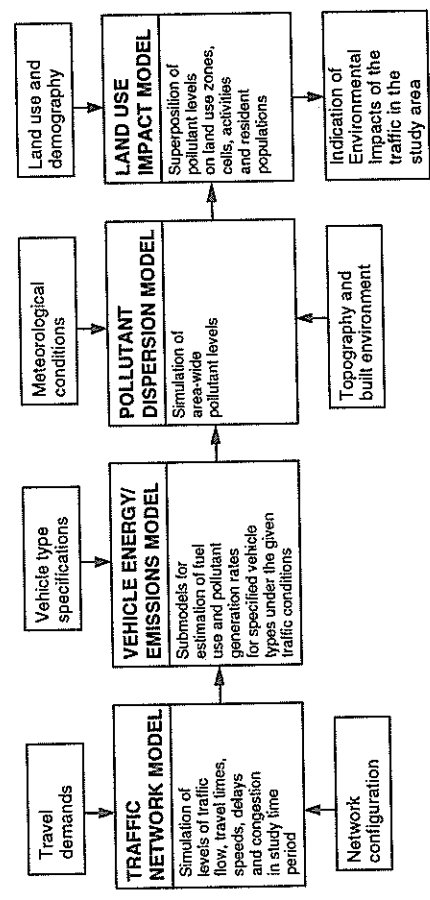


Figure 1: Schematic modelling structure of the IMPAECT supermodel

The application of the IMPAECT system to environmental impact assessment is based on the idea that although the actual levels of pollution across a study area may be affected by many factors besides the transport, meteorological, topological and land use factors included in the component sub-models, the system can reasonably detect differences in pollutant levels between alternative transport plans. The levels of congestion experienced or expected on the transport network for the study region, along with network configuration and capacities, vehicle and fuel technologies, land use distributions and densities have significant effects on the likely emissions of pollutants. Thus modelling procedures for simulating and prediction congestion levels are important constituents of IMPAECT. As IMPAECT is a planning

decision aid, the ability to examine and compare different scenarios relating to the distribution of traffic flows, congestion and patterns of pollutant emissions must also be an important consideration.

MODELS OF TRAFFIC STREAM PERFORMANCE

The traffic stream models comprise three sub-models: (1) sub-models of vehicle energy and emissions performance for different vehicle types under different traffic conditions, (2) congestion functions, to relate travel conditions (delays, queuing and speed-time trajectories) to traffic flows on particular types of roads, and (3) traffic stream composition sub-models, to determine the emissions or fuel consumption of a traffic stream as an aggregate of the vehicles in that stream.

The Biggs-Akcelik Model Family

The Biggs-Akcelik family of models of fuel consumption and emissions 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-Akcelik 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 (perhaps representing a network link), and
- (d) an *average speed model*, that indicates level of emissions or fuel consumption over an entire journey.

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 or land use planning studies which do not include a formal (link-node) description of the transport network can make good use of the average speed model. Thus this family of fuel and emissions models presents a number of alternatives that can be used at a variety of levels of detail in an analysis, and thus offers considerable flexibility for use in transport planning and traffic engineering.

The Instantaneous Model

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 X , including components for:

- the fuel used or emissions generated in maintaining engine operation, estimated by the idle rate (α);
- the work done by the vehicle engine to move the vehicle, and
- 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

$$\begin{aligned} \frac{dE(X)}{dt} &= \alpha + \beta_1 R_T v + \left[\frac{\beta_2 M a^2 v}{1000} \right]_{a>0} & R_T > 0 \\ \frac{dE(X)}{dt} &= \alpha & R_T \leq 0 \end{aligned} \quad (1)$$

where v is speed in ms^{-1} , a is instantaneous acceleration in ms^{-2} , R_T (kN) is the total tractive force required to drive the vehicle, which is the sum of the drag, inertial and grade forces; M is vehicle mass in kg; α is idling fuel consumption or pollutant emission rate; β_1 is an engine efficiency parameter (mL or g per kJ), relating E/C to energy provided by the engine, and β_2 is a second 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

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

where g is the gravitational acceleration in ms^{-2} , G is the percentage gradient (negative downhill); b_1 (kN) is a drag force parameter relating *mainly* to rolling resistance, and b_2 (kgm^{-1}) 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 (Young and Taylor, 1993). The five parameters α , β_1 , β_2 , b_1 and b_2 are specific to a particular vehicle, and the idling rate and energy efficiency parameters (α , β_1 and β_2) depend on the type of fuel or emission as well.

The Elemental Model

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 estimates 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/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_s), road section distance (x_s) and average gradient of the road over the section. The total volume of fuel consumed or pollutant emitted per vehicle over the section ($E_i(X)$) 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:

$$E_i(X) = f_{c1}(x_1 - x_0) + F_d + \alpha t_i + F_a + f_{c2}(x_s - x_1) \quad (3)$$

where f_{c1} and f_{c2} are the cruise E/C rates per unit distance for the initial and final cruise speeds v_{c1} and v_{c2} ; x_1 and x_2 are section distances on approach and departure, respectively; x_s and x_1 are deceleration and acceleration distances, respectively; F_d and F_a are total deceleration and acceleration E/C , respectively; α is the idle E/C rate, and t_i is the idle or stopped time (sec) in the study section.

The elemental model provides estimates of fuel consumption within ten per cent of observed values (Biggs and Akcelik, 1986; Young and Taylor, 1996). 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.

The Running Speed Model

This model may be used for estimation of fuel consumption or emissions along a network link, and is thus the most suitable model for application in a transport network model. The data required to apply the model are travel time t_s (seconds), trip distance x_s (km), and stopped time t_i (seconds) over the route section. The vehicle is then assumed to travel at a constant running speed v_r (km/h), where

$$v_r = \frac{3600x_s}{t_s - t_i} \quad (4)$$

while moving. The model predicts the mean rate of pollution emission or fuel consumption E_s (g or mL per km per vehicle) as

$$E_s = f_r + \frac{a f_i}{x} \quad (5)$$

where f_r is the fuel consumption or pollutant emission per unit distance (mL/km or g/km) excluding stopped time effects (i.e. while cruising at constant speed v_r), and is given by

$$f_r = \frac{3600\alpha}{v_r} + A + Bv_r^2 + k_{e1}\beta_1 + ME_{k+} + k_{e2}\beta_2 ME_{k+}^2 + gk_G\beta_1 M \frac{G}{100} \quad (6)$$

and E_{k+} is the sum of *positive* kinetic energy changes per unit mass per unit distance along the road section (ms^{-2}), which may be estimated from

$$E_{k+} = \max \{0.35 - 0.0025v_r, 0.5\} \quad (7)$$

as described by Biggs and Akcelik (1986). On the basis of empirical results compiled by Biggs and Akcelik, the calibration parameters k_{e1} , k_{e2} and k_G may be estimated from

$$k_{e1} = \max \left\{ 0.675 - \frac{1.22}{v_r}, 0.5 \right\} \quad (8)$$

$$k_{e2} = 2.78 + 0.0178v_r \quad (9)$$

$$k_G = 1 - 1.13E_{k+} \quad \text{for } G < 0 \quad (10)$$

$$k_G = 0.9 \quad \text{for } G > 0$$

A prediction of running speed is needed to complete this link-based model of emissions and consumption, and if this cannot be observed directly then Biggs and Akcelik (1986) indicated that an estimate of the running speed v_r (km/h) may be made from equation (11), given knowledge of the overall average link travel speed $v_s = x/t_i$ (km/h):

$$v_r = \max \{8.1 + 1.14v_s - 0.00274v_s^2, v_s\} \quad (11)$$

This model provides estimates of fuel consumption within 10-15 per cent of observed values for travel over road sections of at least 0.7 km (Biggs and Akcelik, 1986). Road gradient plays a major role in determining the accuracy because of the non-compensatory effects of positive and negative gradients. Longer section lengths will give improved accuracy. The accuracy of

this formula for emissions modelling has yet to be determined. To use the running speed model defined by equations (5)-(11), obtain a predicted link travel time (t_i) from a congestion function (as described below) and then estimate E_{sm} , i.e. the E/C rate for each vehicle type m in the traffic stream (from equations (5)-(10)). The overall E/C rate for the link would then be found by applying the equations given in the section 'traffic stream composition' (see below).

Journey Speed Model

This model is useful for estimating total fuel consumption or emissions over long journeys in large networks, or when no explicit node-link network description is being used (e.g. in a sketch planning application). It would be applied to impact assessment for a regional transport systems management scheme likely to affect mean travel speeds, door-to-door travel times, and the level of traffic demand. It is most applicable for situations in which mean door-to-door travel speeds are 50 km/h or less. Mean travel speed is total travel distance divided by total travel time. The data required are travel distance x , and either total travel time t_i or mean speed v_r . The average speed model relates f_r , the mean consumption or emission rate per unit distance, to the mean travel speed, as follows:

$$f_r = \frac{f_i}{v_r} + b \quad (12)$$

where f_i is the idle E/C rate ($= 3600\alpha$ if v_i is in km/h) and b is a composite parameter accounting for the drag, inertial and grade components of the E/C rate, averaged over the whole journey, written as

$$b = A + Bv_r^2 + k_{e1}\beta_1 ME_{k+} + k_{e2}\beta_2 ME_{k+}^2 + gk_G\beta_1 M\bar{G} \quad (13)$$

where $\bar{G}$ is the mean gradient over the journey and the other parameters are as defined above. The difference between the running speed model and the average speed model is that the latter is a simplified model which assumes that the energy terms contribute a constant amount to fuel consumption and emissions per unit distance. This assumption is valid at low speeds (< 50 km/h), but breaks down at higher speeds where the v_r^2 term dominates. Thus the average speed model tends to underestimate E/C rates at higher speeds. Suitable accuracy in the higher speed range can be achieved by using the running speed model with v_r estimated using equation (11).

Congestion Functions

A number of functional forms relating travel conditions to traffic flows at the link level are available [see Branstetter (1976) and Rose, Taylor and Tisato (1989) for some reviews of such functions]. One suitable function is the Davidson function, which in its most practical form is

$$t = t_0 \left\{ 1 + J \frac{\mu}{1 - \mu} \right\} \quad \mu < \rho \quad (14)$$

$$t = t_0 \left\{ 1 + J \frac{\rho}{1-\rho} + \frac{J}{(1-\rho)^2} (\mu - \rho) \right\} \quad \mu \geq \rho$$

where t is the link travel time, t_0 is the free-flow link travel time, μ is the volume-capacity ratio and J is an environmental parameter that reflects the road type and abutting land use development (and hence the level of friction within the traffic stream). Volume-capacity ratio is defined as the ratio of traffic volume (q) to link capacity (S). The linear extension of the curve for $\mu \geq \rho$ (where $\rho < 1$ is a pre-determined constant, usually in the range (0.85, 0.95)) provides a finite definition of the function for all finite volume-capacity ratios. It also allows for over-saturation of the link (Taylor, 1984). A new function, similar to Davidson's function but based on recent research on delays at traffic signals, has been proposed by Akcelik (1991) and is now finding application in transport network modelling. This function has two attractive features for use in 'dense network' analysis, for it can be applied to the analysis of different turning movements at an intersection and has a time-dependent parameter making it useful for studies where the duration of the peak period demand is of interest. Akcelik's function is

$$t = t_0 \left\{ 1 + \frac{1}{4} r_f (\mu - 1) + \sqrt{(\mu - 1)^2 + \frac{8A}{S_0 r_f} \mu} \right\} \quad (15)$$

where r_f is the ratio of the flow period (T_f) to the minimum travel time t_0 on the link (or movement), and A and S are constants to be determined for a given link class.

The Davidson function provides one example of a relationship between travel time and volume that can be used to influence both the amount of traffic using a link and the emissions and fuel consumption on that link. How this may be done is discussed in Taylor (1995). Alternative forms for congestion functions, such as Akcelik's function, can be used in similar fashion, as demonstrated by Berka and Boyce (1994).

Traffic Stream Composition

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

$$q(e) = \sum_k q_k(e) \quad (16)$$

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 (17):

$$q_m(e) = \sum_k p_{km} q_k(e) \quad (17)$$

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:

$$TE_e(X) = \sum_m E_m(X) p_{em} q_k(e) \quad (18)$$

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

$$TE_e(X) = q(e) \sum_m p_m E_m(X) \quad (19)$$

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

Thus if models can be established to predict $E_m(X)$ for a range of traffic conditions then total pollution loads and fuel consumption can be estimated. These models 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 project has extended the database of available vehicle types, as described later in this paper. 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. This poses some substantial new requirements for data and forecasting, and suitable contemporary data are becoming available (e.g. Woolley and Young, 1994) or can be found by research and investigation using methods such as those described by Biggs and Akcelik (1986).

EXAMPLE E/C MODELS FOR TRAFFIC STREAMS

One set of parameter values for use with the Biggs-Akcelik family of models has been available for some time (Taylor, 1995). This is for Australian passenger cars running on leaded ('super-grade') petrol. It provides models for fuel consumption and emissions of carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides. Table 1 shows the parameter values for a 'representative' (average) vehicle of this type. The current research project has provided data on E/C rates for more recent vehicles. The results of that study are presented in this chapter. In particular, suitable models and parameter values for passenger cars using unleaded fuel were sought. Data were collected for a Toyota Camry sedan with a 2.0 litre four cylinder EFI engine, both on-road and in the laboratory on a chassis dynamometer, and for a Ford Falcon station wagon (4.0 litre six cylinder EFI engine) on-road. The on-road data on fuel consumption were recorded using an inbuilt flow meter in the car (Young and Taylor,

1993). Data on fuel consumption and emissions under controlled conditions were then collected on the dynamometer. Some of the results are described below. These centre on the development of the elemental E/C models for the vehicle.

Table 1: E/C parameters for Australian passenger cars using leaded petrol

Parameter	Fuel	Carbon Monoxide	Carbon Dioxide	Hydrocarbon	Nitrogen Oxides
α (s ⁻¹)	0.444	0.0139	1.0212	0.0022	0.0006
β_1	0.090	0.0150	0.2070	0	0.0010
β_2	0.0300	0.0250	0.1035	0.0004	0.0002
b_1	0.333	0.333	0.333	0.333	0.333
b_2	0.00108	0.00108	0.00108	0.00108	0.00108
M (kg)	1200	1200	1200	1200	1200
Unit	mL/km	g/km	g/km	g/km	g/km

The dynamometer was capable of collecting emissions data on a modal basis; the quantity of each pollutant being measured for each mode of the drive cycle; namely acceleration, deceleration, cruise and idle modes. Modal emissions data can help provide an understanding of the relationship between driving conditions and exhaust emission rates. The vehicle was driven over the cold-start transient phase, the stabilised phase and the hot-start transient phase of the AS 2877 city cycle. The 'cold-start' transient and stabilised phases were repeated while the car was warm, to check that the results being obtained were stable, before proceeding with the 'controlled' tests. The dynamometer was used to collect second-by-second data for a series of controlled emissions tests. The controlled emissions tests included cruise (steady-speed) tests that were performed for speeds from 10 km/h to 100 km/h in 10 km/h increments. Two readings were taken for each speed increment. Full details of the data collection procedures and the methods for deriving the model parameters from the observed data are described in Young and Taylor (1996).

MODELS FOR THE TOYOTA CAMRY

The description of model development presented in this paper focuses on the elemental model, and the estimation of submodels for fuel consumption and emissions of carbon dioxide and carbon monoxide for the idling, cruising, acceleration and deceleration modes.

Cruise (Steady Speed) Models

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 steady cruise speed fuel consumption model was

$$\dot{f}_{c,i} = 0.294 + 0.0311v + 0.000004v^3 \quad (20)$$

for speed v in m/s. The steady-speed data from the dynamometer tests was also used to develop a cruise fuel consumption model for the Toyota Camry. The model, of the same form as equation (20), was found to be:

$$\dot{f}_{c,r} = 0.294 + 0.0324v + 0.000005v^3 \quad (21)$$

with the constant term fixed to the idle fuel consumption rate as given above. The regression curve ($R^2 = 0.990$) is shown in Figure 2 with the dynamometer data and the curve for on-road cruise fuel consumption as well.

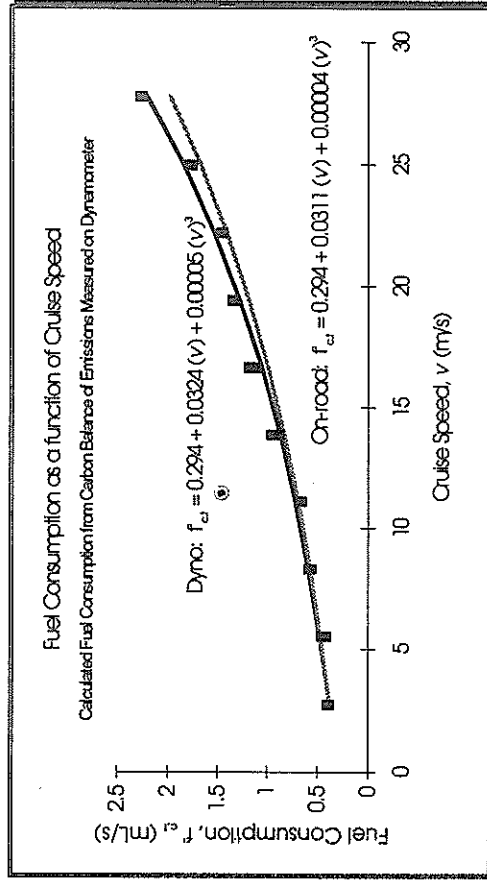


Figure 2: Cruise fuel consumption rate as a function of cruise speed (Toyota Camry)

As noted in the above figure, the fuel consumption was not measured directly during emissions testing on a dynamometer, but was calculated using the carbon balance method. This procedure involves converting the carbon in the exhaust gases (CO_2 , CO and HC) to an equivalent volume of fuel. Since the majority of carbon in the exhaust gases is contained in the carbon dioxide, the exhaust emission rate for carbon dioxide is highly correlated to the fuel consumption rate of any particular vehicle. Hence it makes sense to use the same form of model for fuel consumption and carbon dioxide emissions.

The steady-speed emissions data from the dynamometer was thus used to develop a model of the same form as equation (21) for the carbon dioxide emission rate, $E(\text{CO}_2)_c$, as a function of cruise speed, v . The constant term is fixed at the idle carbon dioxide emission rate which was found to be 0.799 g/s on average. The coefficient of determination, R^2 for the resulting

regression model was calculated to be 0.987. The model is given in equation (22) and the emissions data with the fitted model is shown in Figure 3.

$$E(\text{CO}_2)_c = 0.799 + 0.0625 v + 0.00012 v^3 \quad (22)$$

It is clear that the curve for carbon dioxide emissions is of a very similar shape to the curve for fuel consumption (Figure 2) for steady-speed driving.

Steady-speed emissions data was also collected for hydrocarbons, carbon monoxide and nitric oxides. A plot of the carbon monoxide emissions rates as a function of cruise speed is shown in Figure 4.

Clearly the relationship between emission rate and cruise speed for carbon monoxide emissions is not as obvious as that for carbon dioxide. 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 . The plot in Figure 4 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 would be 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 was found to be described by:

$$E(\text{CO})_c = 0.007 + 0.0007v + 0.0009v^2 - 0.00009v^3 \quad [0 \leq v \leq 11.2 \text{ m/s}] \quad (23)$$

and

$$E(\text{CO})_c = 0.0022 - 0.0002v + 0.000005v^2 \quad [v > 11.2 \text{ m/s}] \quad (24)$$

The cubic and quadratic curves intersect at a speed of $v = 11.2$ m/s and hence equation (23) should be applied for speeds up to and equal to 11.2 m/s and equation (24) should be used beyond this. The two curve segments described by equations (23) and (24) are shown superimposed over the data points in Figure 4. These functions are not claimed to be ideal models; they simply attempt to describe the data obtained for the Toyota Camry on the dynamometer. There is a need for further research to be done in this area of cruise emissions modelling. In particular, it would be worthwhile repeating similar cruise tests with greater control over the temperature of the engine and catalytic converter. By monitoring the temperature of the catalytic converter it would be possible to select a temperature to which the converter could be cooled to, before recording the cruise emission rates for any given speed.

Acceleration Phase Models

Emissions data were also collected for acceleration phases, for accelerations from rest to 100 km/h at a range of acceleration rates. The rates used were 2 km/h/s to 6 km/h/s, in increments of 1 km/h/s. The data collected during the acceleration tests were used to develop acceleration fuel consumption functions of the same form as those developed from the on-road data. The form of the acceleration fuel consumption functions is:

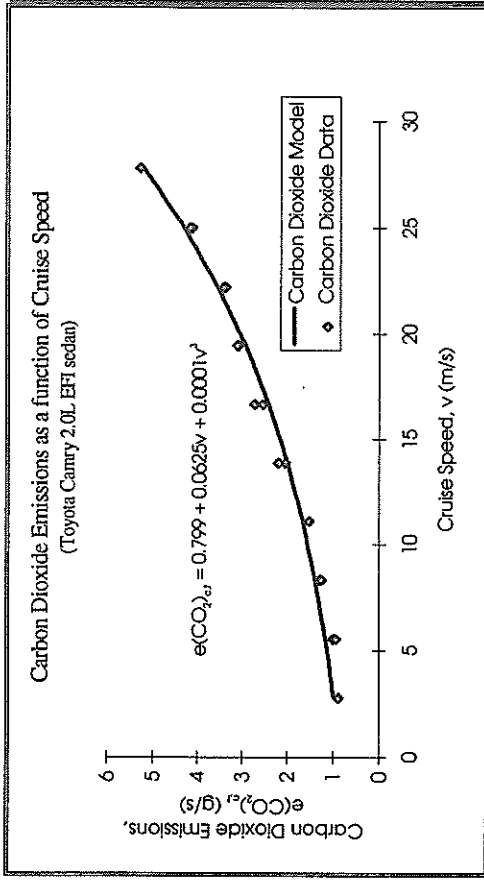


Figure 3: Cruise carbon dioxide emissions and cruise speed (Toyota Camry)

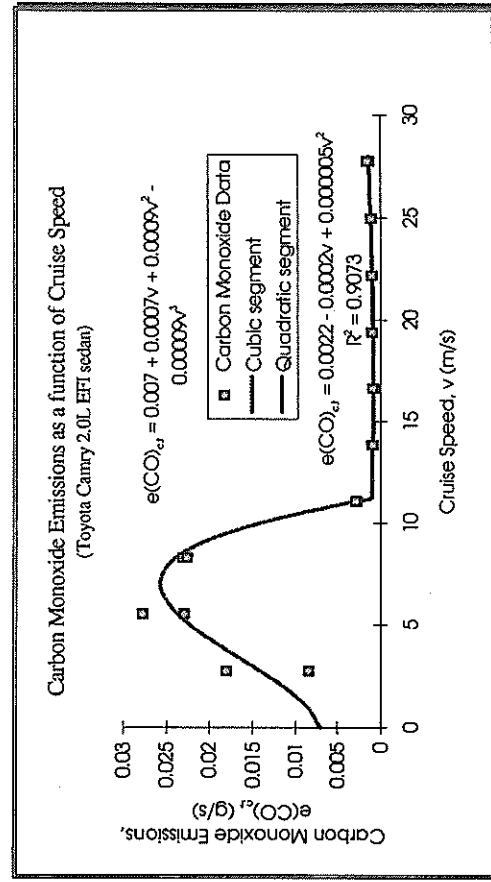


Figure 4: Cruise carbon monoxide emissions and cruise speed (Toyota Camry)

$$F_a = Av_f + Bv_f^2 \tag{25}$$

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. An on-road acceleration fuel consumption function was developed for all acceleration rates and separate functions were developed for four sub-sets of data; each set with a range of acceleration rates spanning only 1 km/h/s (e.g. 1.5 km/h/s - 2.5 km/h/s; 2.5 km/h/s - 3.5 km/h/s; ... 4.5 km/h/s - 5.5 km/h/s). The acceleration rates here are average rates for each acceleration phase ($\Delta v/\Delta t$), as opposed to instantaneous acceleration rates. These curves are shown in Figure 5, while Table 2 gives the coefficients (A and B) of the functions and the coefficients of determination, R^2 for each acceleration rate.

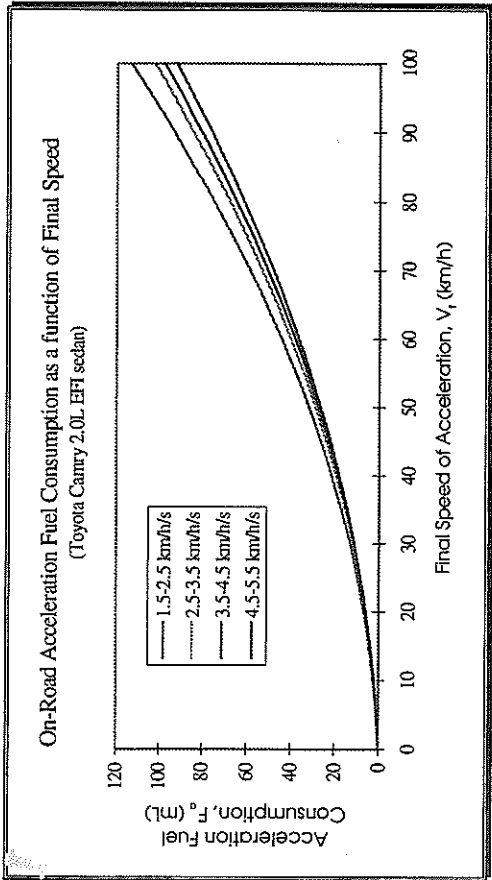


Figure 5: Acceleration fuel consumption as a function of final speed of acceleration and acceleration rate (Toyota Camry, on-road data)

Table 2: Model coefficients for on-road acceleration fuel consumption functions (Figure 5), Toyota Camry

Acceleration Rate (km/h/s)	Coefficient of v_f , A	Coefficient of v_f^2 , B	Coefficient of Determination, R^2
1.5-2.5	0.4736	0.1302	0.999
2.5-3.5	0.4317	0.1175	0.999
3.5-4.5	0.3933	0.1129	0.999
4.5-5.5	0.4613	0.1029	0.999
all rates	0.4089	0.1182	0.994

It is interesting to note that for an acceleration to any final speed, v_f the fuel consumed decreases with increasing acceleration rate. There are two principles at work which influence the amount of fuel consumed, in opposite directions. Firstly, at any speed the fuel consumption rate (in terms of volume per time or volume per distance) increases with acceleration rate. However, the opposing principle is that a higher acceleration rate results in less time to reach the desired speed and also less distance travelled. Hence, although the fuel consumption rate is greater, the reduced time (or distance) has a stronger influence on the total fuel consumed. Hence the net effect is a reduction on the total fuel consumed. The way in which these models should be applied will depend on the information known and the degree of accuracy required. Where a specific acceleration rate is known or assumed, the model for the appropriate range of acceleration rates should be applied. If the acceleration rate is not known and no specific rate is assumed, one of two approaches may be taken:

- (1) the model developed for all rates may be applied (the average acceleration rate for all the data from the on-road controlled tests was 3.4 km/h/s; and 3.2 km/h/s for the dynamometer controlled tests), or
- (2) the model developed for acceleration rates between 3.5 km/h/s and 4.5 km/h/s may be applied. This range is representative of typical urban acceleration rates in Adelaide, South Australia, where the on-road data were collected.

The acceleration fuel consumption data from the controlled tests on the dynamometer are shown in Figure 6. These data are for the full range of acceleration rates. Figure 7 shows a set of curves for the acceleration fuel consumption functions determined from the dynamometer data, and Table 3 provides coefficients for these functions which can be compared with those in Table 2. The coefficients for the model developed from the complete data set (i.e. for the full range of acceleration rates) are also given in this table.

One of the observations that can be made by examination of Figures 6 and 7 is that the variation in fuel consumption due to acceleration rate is greater for the dynamometer data than the on-road data.

Table 3: Model coefficients for dynamometer acceleration fuel consumption functions (Figure 7), Toyota Camry

Acceleration Rate (km/h/s)	Coefficient of v_f , A	Coefficient of v_f^2 , B	Coefficient of Determination, R^2
1.5-2.5	0.5772	0.1317	0.999
2.5-3.5	0.5553	0.1110	0.999
3.5-4.5	0.5229	0.0952	0.987
4.5-5.5	0.5844	0.0868	0.986
all rates	0.6068	0.1043	0.976

The form of the fuel consumption function for acceleration phases, as in equation (25), was also found to be ideal for modelling acceleration carbon dioxide emissions, $E(\text{CO}_2)$.

$$E(\text{CO}_2)_a = Av_f + Bv_f^2 \tag{26}$$

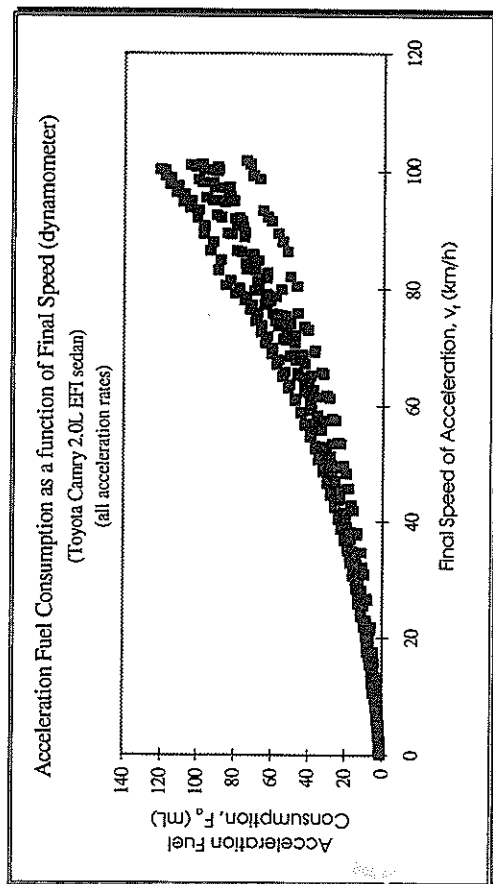


Figure 6 Acceleration fuel consumption data as a function of final speed of acceleration (dynamometer data, Toyota Camry)

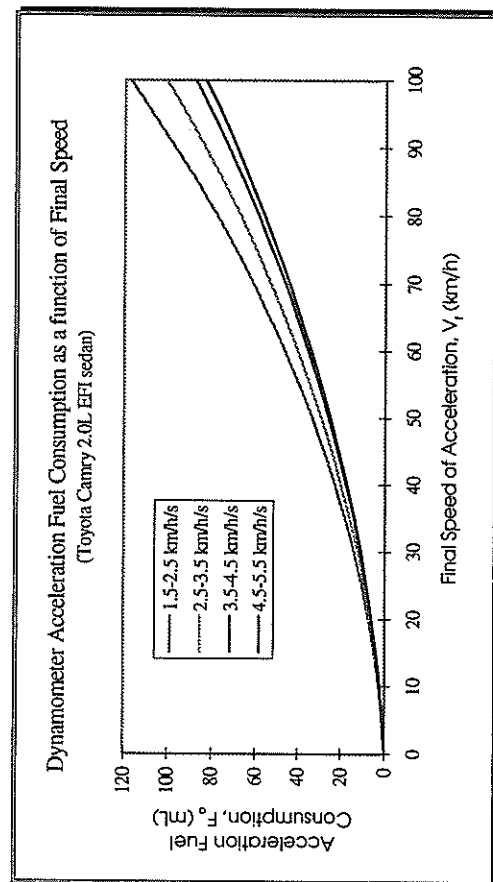


Figure 7: Acceleration fuel consumption as a function of final speed of acceleration and acceleration rate (dynamometer data, Toyota Camry)

where $E(\text{CO}_2)_a$ is the acceleration CO_2 emissions, in grams (for accelerations from rest to v_f).

Table 4 gives coefficients for a general acceleration carbon dioxide function (developed for the full range of acceleration rates) and coefficients for the four functions developed for limited ranges of acceleration rates (as described earlier). The functions are shown graphically in Figure 8. The full data set of carbon monoxide emissions for the controlled acceleration tests on the dynamometer is shown in Figure 9.

Table 4 Model coefficients for acceleration carbon dioxide emissions functions (Figure 8), Toyota Camry

Acceleration Rate (km/h/s)	Coefficient of v_f , A	Coefficient of v_f^2 , B	Coefficient of Determination, R^2
1.5-2.5	1.9896	0.0798	0.998
2.5-3.5	1.4550	0.0712	0.999
3.5-4.5	1.7381	0.0607	0.999
4.5-5.5	2.2596	0.0502	0.999
all rates	1.8977	0.0651	0.985

The functional form that was found to best describe the acceleration carbon monoxide emissions, $E(\text{CO})_a$, data was an exponential function of the type given by equation (27).

$$E(\text{CO})_a = A e^{Bv_f} \quad (27)$$

The model coefficients A and B determined for each acceleration range and for all the data are given in Table 5. Figure 10 shows the shape of each regression curve for the acceleration carbon monoxide emissions data. The overall regression curve is also included in Figure 9.

Table 5 Model coefficients for acceleration carbon monoxide emissions functions (Figure 10), Toyota Camry

Acceleration Rate (km/h/s)	Constant term, A	Coefficient of v_f , B	Coefficient of Determination, R^2
1.5-2.5	0.0211	0.2024	0.977
2.5-3.5	0.0112	0.2260	0.926
3.5-4.5	0.0126	0.2562	0.970
4.5-5.5	0.0754	0.1978	0.965
all rates	0.0181	0.2343	0.735

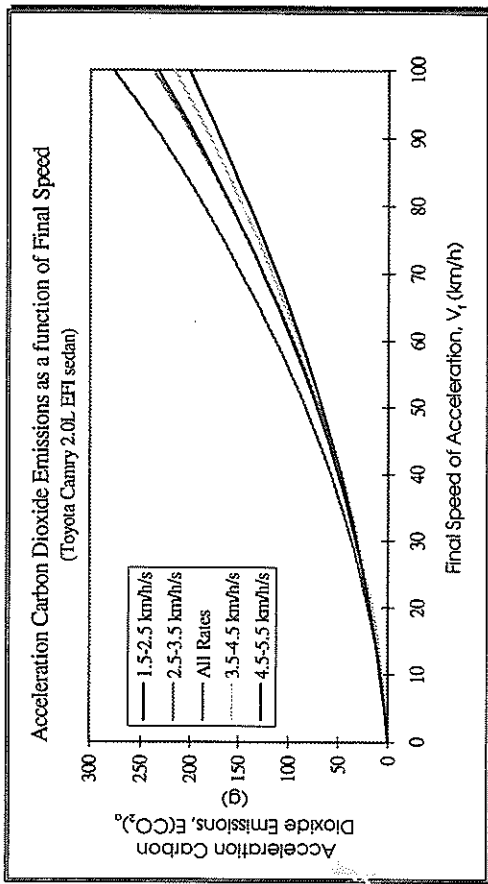


Figure 8: Acceleration carbon dioxide emissions as a function of final speed of acceleration and acceleration rate (Toyota Camry)

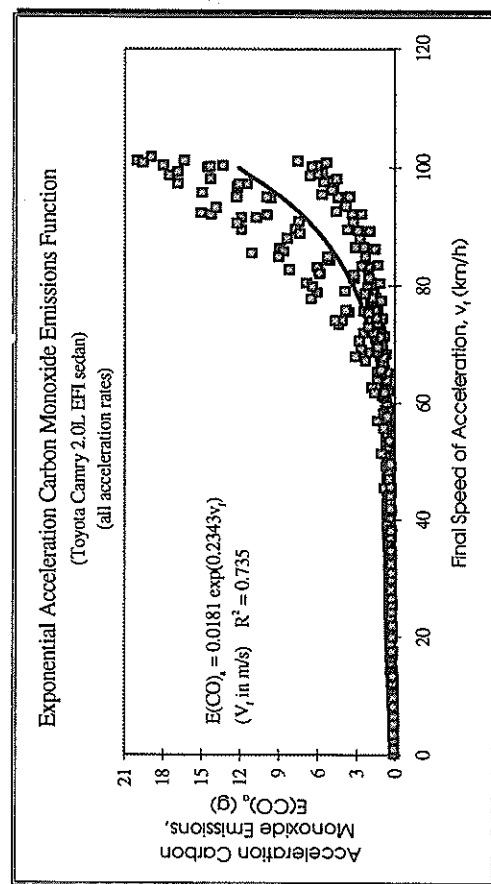


Figure 9: Acceleration carbon monoxide emissions data as a function of final speed of acceleration (Toyota Camry)

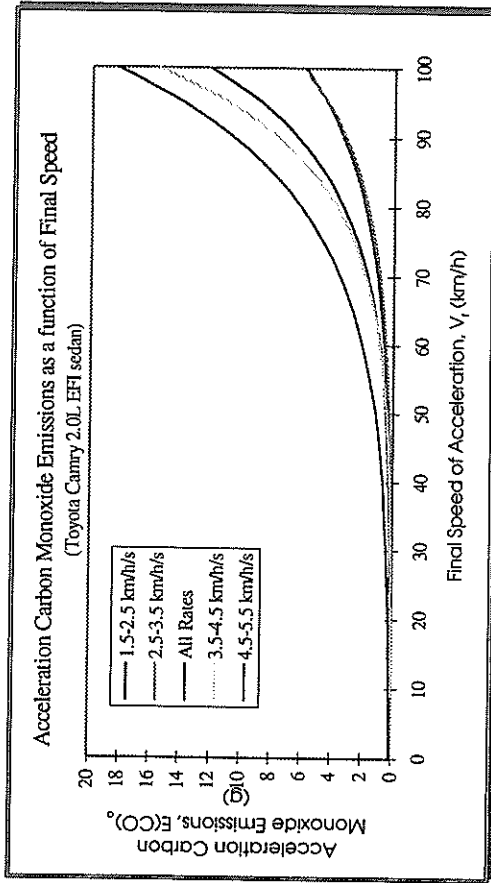


Figure 10: Acceleration carbon monoxide emissions as a function of final speed of acceleration and acceleration rate (Toyota Camry)

MODELS FOR THE FORD FALCON

The Toyota Camry was replaced by a Ford Falcon at the end of 1993, close to the end of the data collection phase of the research project. The Ford Falcon is a six-cylinder four-litre electronic fuel injected (EFI) wagon with automatic transmission. The amount of data collected with the second instrumented vehicle was significantly less than for the Camry - dynamometer tests were not possible in the project time frame. However, the Falcon was used to obtain useful on-road urban driving data and data for controlled tests similar those carried out for the Camry. Acceleration, deceleration and cruise fuel consumption models were developed for the Falcon and vehicle parameters for the Biggs-Akcelik fuel consumption models were determined.

Idle fuel consumption rate

The idle fuel consumption rate, α , for the Ford Falcon was found to be $\alpha = 0.500 \text{ mL/s}$ (Young and Taylor, 1996).

Cruise (steady-speed) fuel consumption

The 'controlled' tests included cruise tests at steady-speed for the determination of parameters for the cruise fuel consumption model as described for the Toyota Camry. The Ford Falcon was driven at cruise speeds of 10 km/h to 110 km/h in increments of 10 km/h and second-by-second speed profile and fuel consumption data were collected. Figure 11 shows the data

obtained from these cruise speed tests. A cubic regression curve was fitted to the data. The coefficient of determination, R^2 for this curve was found to be 0.995. The curve is shown in Figure 12, together with the curve for the Toyota Camry (see also Figure 2) for comparison. The fitted curve for the Ford Falcon was

$$f_{c,1} = 0.500 + 0.049v + 0.00005v^3 \tag{28}$$

where $f_{c,1}$ is the constant-speed cruise fuel consumption, in mL/s, and v is the instantaneous speed, in m/s. Table 6 shows the values determined for c_1 and c_2 for the Ford Falcon and the values for the Toyota Camry.

Table 6: Cruise Fuel Consumption Parameters for Ford Falcon and Toyota Camry

Parameter	Ford Falcon	Toyota Camry
c_1 (mL/m)	0.049	0.031
c_2 (mL/m)/(m/s) ²	4.94E-05	3.84E-05

Acceleration fuel consumption

Acceleration phases from rest up to speeds of 110 km/h were tested for acceleration rates of 2 km/h/s to 5 km/h/s in increments of 1 km/h/s. These tests resulted in over 1600 data points to which the regression curve shown in Figure 13 was fitted. The computed regression curve was:

$$F_a = 0.6186v_f + 0.1564v_f^2 \tag{29}$$

where F_a is the acceleration fuel consumption, in mL, (for an acceleration from rest to v_f); and v_f is the final speed of the acceleration phase, in m/s. A value of 0.989 was found for the coefficient of determination of this regression curve. The width of the band of data points is due to the range of acceleration rates included in the testing.

Table 7: Model Coefficients for Acceleration Fuel Consumption Functions (Ford Falcon, Figure 14)

Acceleration Rate (km/h/s)	Coefficient of v_f , A	Coefficient of v_f^2 , B	Coefficient of Determination, R^2
1.5-2.5	0.6322	0.1861	0.996
2.5-3.5	0.7176	0.1619	0.996
3.5-4.5	0.6700	0.1480	0.997
4.5-5.5	0.3919	0.1569	0.997
5.5-6.5	0.0328	0.1734	0.995
all rates	0.6186	0.1564	0.989

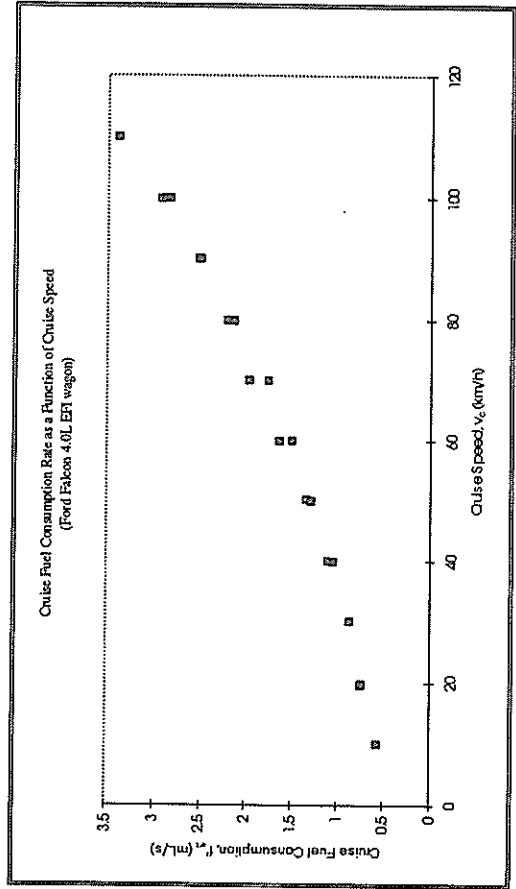


Figure 11: Cruise fuel consumption rate as a function of cruise speed (Ford Falcon)

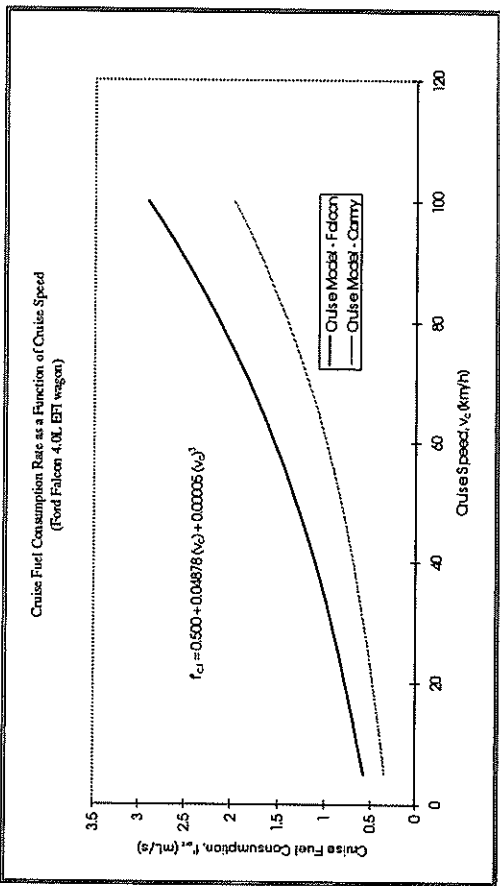


Figure 12: Cruise fuel consumption models - Ford Falcon and Toyota Camry

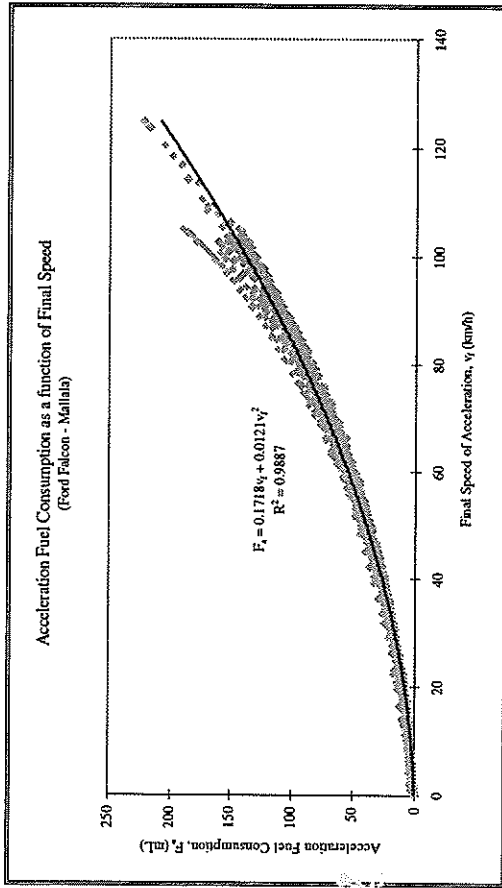


Figure 13: Acceleration fuel consumption and final speed of acceleration (Ford Falcon)

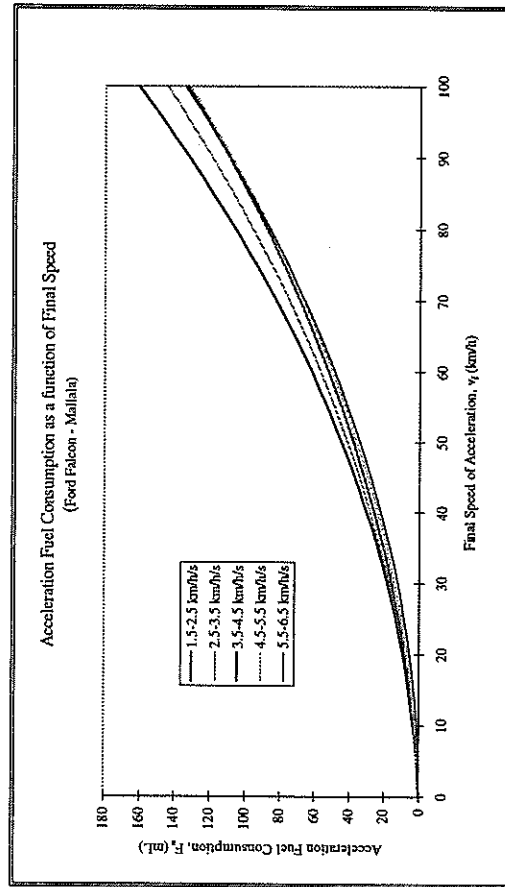


Figure 14: Acceleration fuel consumption as a function of final speed of acceleration and acceleration rate (Ford Falcon)

Separate models were determined for five sets of data; each set with a range of acceleration rates spanning 1 km/h/s (e.g. 1.5 km/h/s - 2.5 km/h/s; 2.5 km/h/s - 3.5 km/h/s; ... 5.5 km/h/s - 6.5 km/h/s). The resulting set of curves, presented in Figure 14, shows the difference in fuel consumption for the range of acceleration rates. The acceleration rates here are average rates for each acceleration phase ($\Delta v/\Delta t$; where Δv is equal to $v_f - v_i$ and $v_i = 0$ for these curves; and Δt is the length of the phase in units of time), as opposed to instantaneous acceleration rates.

Urban Driving Data Collection

The Ford Falcon was used to collect travel time, speed profile and fuel consumption data along Adelaide's Main North Road (a divided arterial with two lanes in each direction and two relatively short sections of three lanes). This road is the major arterial road from the northern suburbs into the Adelaide CBD. A section of some 20 km, from the Barton Terrace intersection in North Adelaide to John Rice Avenue, Salisbury was surveyed. The data collection was carried out in both directions during different times of day. The test route was divided into ten links, as specified in Table 8 below. The links are shown for the route when travelling north; for a southbound trip the link numbers are reversed. The Main North Road test route is speed zoned into 60 km/h, 70 km/h, 80 km/h and 100 km/h sections (see Table 8 and Figure 15 for details).

Table 8: Definition of links on Main North Road

Link Number	Start of Link	Speed Zones (km/h)	Number of Lanes
1	Main North Road/Barton Terrace	60	2
2	Main North Road/Fitzroy Terrace	60	2
3	Main North Road/Nottage Terrace	60	2
4	Main North Road/Regency Road	60	2
5	Main North Road/Grand Junction Road	80-70	2-3
6	Main North Road/Montague Road	80-100	2
7	Main North Road/Kings Road	80	2
8	Main North Road/Frost Road	80	2
9	Main North Road/Park Terrace	80	2
10	Main North Road/Sains Road	80	2
End of route	Main North Road/John Rice Avenue		2-3

Figure 16 shows a typical speed-time profile with the cumulative fuel consumption curve for travel observed along the Main North Road route. On-road profiles of this kind were used to determine the parameters for the Biggs-Akcelik fuel consumption models, using the procedure described in Young and Taylor (1996). The complete parameter set for the Ford Falcon is shown with the corresponding parameters for the Toyota Camry in Table 9. Both of these vehicles run on unleaded fuel and have EFI engines.

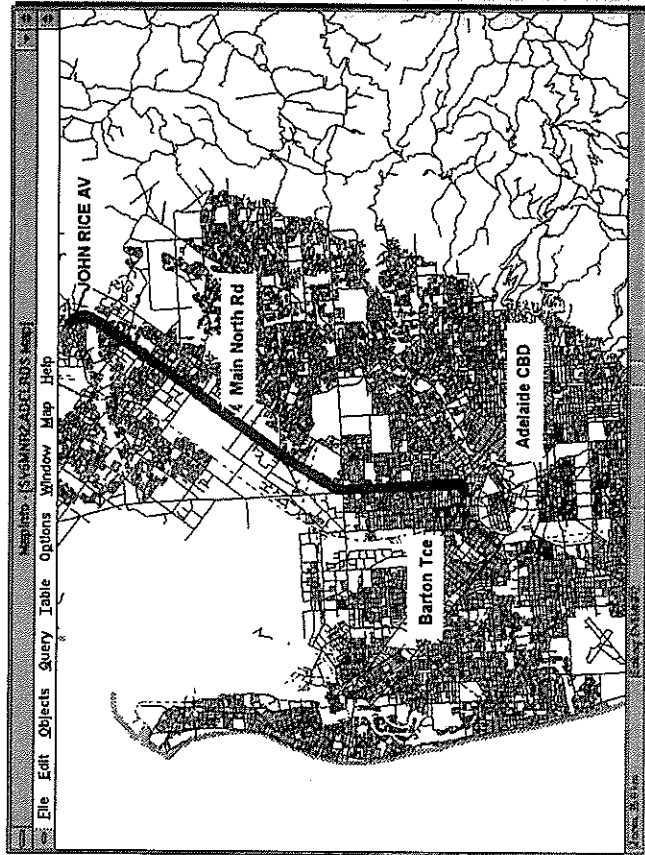


Figure 15: Map of Northern Metropolitan Adelaide showing the Main North Road Route

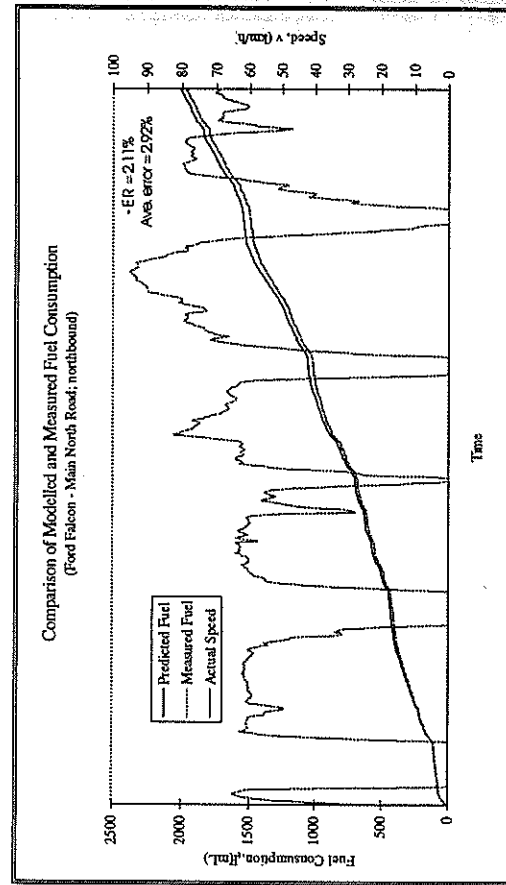


Figure 16: Speed profile for Ford Falcon showing performance of instantaneous model

Table 9: Fuel Consumption Parameters for Ford Falcon and Toyota Camry

Parameter	Ford Falcon (4.0 L EFI, unleaded fuel)	Toyota Camry (2.0 L EFI, unleaded fuel)	Standard Australian car (pre-1985, leaded fuel)
α	0.500	0.294	0.444
β_1	0.094	0.068	0.090
β_2	0.031	0.041	0.030
b_1	0.517	0.455	0.333
b_2	0.00160	0.00056	0.00108
M	1850	1250	1200

1. as given in Taylor (1995)

The Biggs-Akcelik instantaneous model was applied with these parameters to the speed profile shown in Figure 15 with the appropriate road grade data (see Young and Taylor (1996)). This data sets 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, ER is defined as the sum of the errors for each data record, divided by the total measured fuel consumption. Figure 15 shows a plot of the cumulative predicted fuel consumption as well as the measured cumulative fuel consumption and the speed profile.

CONCLUSIONS

Environmental impact analysis is an important component of modern transport planning practice and there is a need for analytical procedures and models for its incorporation in transport network analysis. A modelling structure for such incorporation was introduced in this paper, in the form of the IMPAECT supermodel. An important component of IMPAECT is a module for fuel consumption and emissions by traffic streams. The paper described a family of models for estimating fuel consumption and pollutant emissions by vehicles in a traffic stream. The family presents a number of alternative models that can be used at a variety of levels of detail in an analysis, and thus offers considerable flexibility for use in transport planning and traffic engineering. The means for applying the models in transport planning is described in Taylor (1995).

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MULTI SENSOR, MULTIVARIATE, AND MULTI-CLASS INCIDENT DETECTION SYSTEM FOR ARTERIAL STREETS

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ABSTRACT

A novel approach to incident detection on arterial that utilizes multi-sensor, multi-class, and multivariate classifiers to differentiate between various traffic states is proposed. The similarities between the Bayes' fusion of multi-sensor allocations and Multiple Attribute Decision Making (MADM) are established. An array of MADM algorithms is thus made available to the traffic engineer for purposes of fusion of multi-sensor allocations. One such algorithm is applied to the detection of incidents on arterial streets using detector occupancies and vehicle counts by lane, probe travel times, and probe report numbers as attributes. The probe data proves valuable in enhancing the performance of detector data based models. Models based solely on probe data lack in performance, due to excessive overlaps in class distributions. The possibilities for identifying incidents through their flow imbalance impacts, using multivariate detector classifiers, prove promising.

1 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 and the Intermodal Surface Transportation Environmental Act (ISTEA) of 1991 have urged a shift in the United States' approach to controlling the growing traffic congestion. The use of advanced techniques is encouraged to promote the efficient use of existing facilities rather than build new facilities. Much of the congestion suffered on roadway networks is nonrecurring and caused by incidents. In 1987, about 60% of freeway delays were believed due to incidents (Lindley, 1987). An incident consists of any event that temporarily reduces the capacity of a roadway. Advanced techniques which seek to decrease the congestion impacts of incidents thus satisfy a need identified by recent legislation.

Automated Incident Detection (AID) algorithms contain the congestion induced by incidents through the enhancement of the detection process. They monitor the flow of traffic