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TOPIC 18
ENVIRONMENT AND
SUSTAINABLE MOBILITY

MODELLING EMISSIONS AND FUEL CONSUMPTION FOR ROAD TRAFFIC STREAMS

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Abstract

The paper discusses a family of models of vehicle fuel consumption and pollutant emissions for transport planning and traffic engineering applications. It then describes a series of on-road and laboratory experiments using an instrumented car to provide parameter values for use with these models.

INTRODUCTION

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 vehicle testing, both on-road and in the laboratory, to measure fuel consumption and emissions. A set of models was then assembled. These models may then be used into transport network analysis, for the prediction of environmental and energy impacts of road transport projects. One such integration of the models into a super-model for environmental impact analysis of transport planning decisions is described.

A SUPER-MODEL FOR ENVIRONMENTAL IMPACT ANALYSIS

A long-standing problem in transport planning and decision-making has been how to assess the relative effects, merits and disadvantages of alternative transport infrastructure proposals, especially in terms of the environmental impacts. Survey methods for assessing levels of pollution are available for the study of existing conditions, eg Taylor, Young and Bonsall (1995). These methods cannot be applied to proposed developments, and alternative means for the appraisal of alternatives are required. One such decision-support tool is the IMPAECT (Impact Model for the Prediction and Assessment of the Environmental Consequences of Traffic) super-model. IMPAECT 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 basic structure of IMPAECT is shown in 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.

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. The modelling approach means that a number of pollutants can be included together under the same sets of conditions, eg noise, gaseous emissions, and fine particulates. Thus alternative transport schemes may be ranked on a number of environmental quality objectives, and comparisons made between them.

A full description of the IMPAECT super-model is available in Woolley and Young (1994). The set of traffic network models it utilises are described in Taylor and Anderson (1988) and Taylor (1995), and details of the pollutant dispersion model are given in Thompson-Clement, Woolley and Taylor (1995). This paper concentrates on 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.

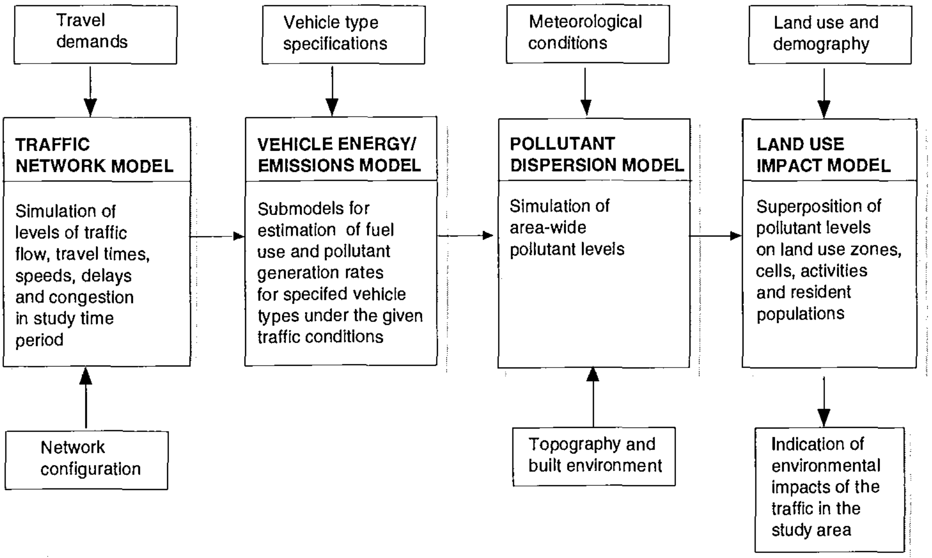

Figure 1 **Structure of the IMPAECT Super-Model and its broad data requirements**

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, eg through traffic and local traffic, private, commercial and business travel, etc. If q(e) is the total vehicle volume on link e then

$$q(e) = \sum_k q_k(e) \tag{1}$$

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 (2):

$$q_m(e) = \sum_k p_{km} q_e(k) \tag{2}$$

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:

$$TE_e(X) = \sum_{km} E_m(X) p_{km} q_k(e) \tag{3}$$

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

$$TE_e(X) = q(e) \sum_m p_m E_m(X) \tag{4}$$

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 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.

Congestion functions

A number of functional forms relating travel conditions to traffic flows at the link level are available [see 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

$$
\begin{aligned}
t &= t_0\left\{1 + J\frac{\mu}{1-\mu}\right\} & \mu < \rho \\
t &= t_0\left\{1 + J\frac{\rho}{1-\rho} + \frac{J}{(1-\rho)^2}(\mu-\rho)\right\} & \mu \geq \rho
\end{aligned} \qquad (5)
$$

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 viable definition of the function for all finite volume-capacity ratios. It also allows for over-saturation of the link (Taylor 1984).

Functions such as this suggest relationships 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.

THE BIGGS-AKCELIK HIERARCHY

A family of four models of fuel consumption and emissions modelling was proposed by Biggs and Akcelik (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-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 (eg 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 which do not include a formal (link-node) description of the transport network can make good use of the average speed model.

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:

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

(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

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

$$\frac{dE(X)}{dt} = \alpha \qquad R_T \leq 0 \tag{6}$$

where

v = speed (ms^{-1}),

a = instantaneous acceleration in ms^{-2},

R_T = total tractive force required to drive the vehicle, which is the sum of the drag, inertial and grade forces

M = vehicle mass in kg;

α = idling fuel consumption or pollutant emission rate;

β_1 = engine efficiency parameter (mL or g per kJ), relating E/C to energy provided by the engine, and

β_2 = 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

$$R_T = b_1 + b_2 v^2 + \frac{Ma}{1000} + g\left(\frac{M}{1000}\right)\left(\frac{G}{100}\right) \tag{7}$$

where

g = gravitational acceleration in ms^{-2};

G = percentage gradient (negative downhill);

b_1 = drag force parameter relating *mainly* to rolling resistance, and

b_2 = 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 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.

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:

(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_i), 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 ($E_s(X)$) 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:

$$E_s(X) = f_{c1}(x_{s1} - x_d) + F_d + \alpha t_i + F_a + f_{c2}(x_{s2} - x_a) \tag{8}$$

where

f_{c1}, f_{c2} = cruise E/C rate per unit distance for the initial and final cruise speeds v_{c1} and v_{c2}.

x_{s1}, x_{s2} = section distances on approach and departure, respectively

x_d, x_a = deceleration and acceleration, respectively

F_d, F_a = total deceleration and acceleration E/C, respectively

α = idle E/C rate

t_i = idle or stopped time (sec)

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 (eg an intersection) rather than on those of individual vehicles traversing that element.

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 c_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

$$v_r = \frac{3600 x_s}{t_s - t_i} \tag{9}$$

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

$$E_s = f_r + \frac{\alpha t_i}{x_s} \tag{10}$$

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

$$f_r = \frac{3600\alpha}{v_r} + A + B v_r^2 + k_{E1}\beta_1 + M E_{k+} + k_{E2}\beta_2 M E_{k+}^2 + g k_G \beta_1 M \frac{G}{100} \tag{11}$$

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

$$E_{k+} = \max\{0.35 - 0.0025 v_r, 0.5\} \tag{12}$$

as described by Biggs and Akcelik (1986). The calibration parameters k_{E1}, k_{E2} and k_G are found from:

$$k_{E1} = \max\left\{0.675 - \frac{1.22}{v_r}, 0.5\right\} \tag{13}$$

$$k_{E2} = 2.78 + 0.0178 v_r \tag{14}$$

$$\begin{aligned} k_G &= 1 - 1.13 E_{k+} && \text{for } G < 0 \\ k_G &= 0.9 && \text{for } G > 0 \end{aligned} \tag{15}$$

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 (16), given knowledge of the overall average link travel speed $v_s = x_s/t_s$ (km/h):

$$v_r = \max\{8.1 + 1.14 v_s - 0.00274 v_s^2, v_s\} \tag{16}$$

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. Longer section lengths will give improved accuracy. To use the running speed model defined by equations (10)-(16), the transport analyst would obtain a predicted link travel time (t_s) from a congestion function (eg equation (5)) and then estimate E_{sm}, ie the E/C rate for each vehicle type m in the traffic stream (from equations (10)-(15)). The overall E/C rate for the link would then be found by applying equations (3) or (4).

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 (eg in a sketch planning application). It would be apply 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_s, and either total travel time t_s or mean speed v_s. The average speed model relates f_x, the mean consumption or emission rate per unit distance, to the inverse of the mean travel speed:

$$f_x = \frac{f_i}{V_s} + b \tag{17}$$

where f_i is the idle E/C rate (= 3600α if v_s 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, and written as

$$b = A + Bv_r^2 + k_{E1}\beta_1 ME_{k+} + k_{E2}\beta_2 ME_{k+}^2 + gk_G\beta_1 M\overline{G} \tag{18}$$

where $\overline{G}$ 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.

EXAMPLES OF 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' vehicle of this type.

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

A research study to provide data on E/C rates for more recent vehicles has been undertaken by the authors, and some of the results of that study are presented below. In particular, suitable models and parameter values for passenger cars using unleaded fuel have been sought. Data were collected for a Toyota Camry sedan with a 2.0 litre EFI engine, both on-road and in the laboratory on a chassis dynamometer. 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. 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.

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, while the steady cruise speed fuel consumption model was

$$f'_{c,t} = 0.294 + 0.0311v + 0.00004v^3 \qquad (19)$$

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. This model, of the same form as equation (19), was:

$$f'_{c,t} = 0.294 + 0.0324\, v + 0.00005\, v^3 \qquad (20)$$

with the constant term fixed to the idle fuel consumption rate as 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. As noted in Figure 2, the fuel consumption is not measured directly during emissions testing on a dynamometer, but is 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 (20) for the carbon dioxide emission rate, $E(CO_2)_c$ 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 (21) and the emissions data with the fitted model is shown in Figure 3.

$$E(CO_2)_c = 0.799 + 0.0625\, v + 0.00012\, v^3 \qquad (21)$$

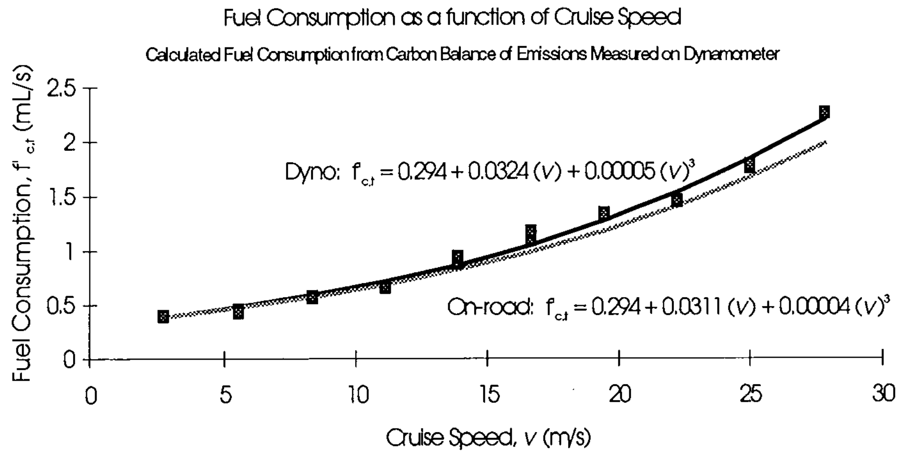

Figure 2 **Cruise fuel consumption rate as a function of cruise speed**

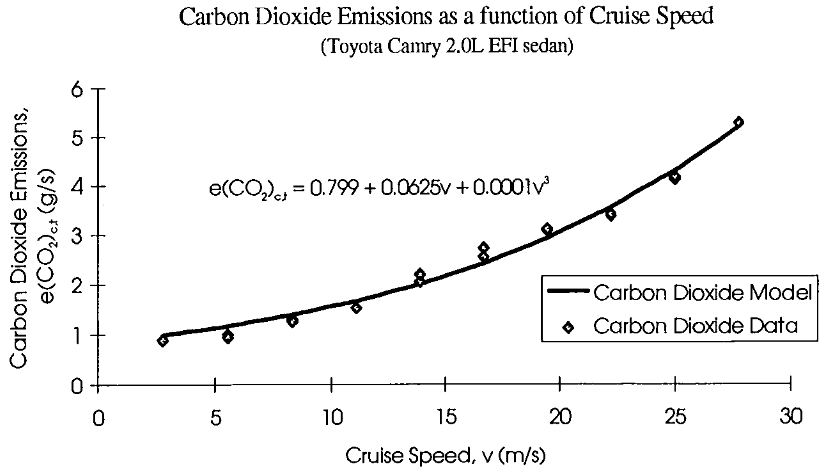

Figure 3 **Cruise carbon dioxide emissions as a function of cruise speed**

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. 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:

$$E(CO)_{c,} = 0.007 + 0.0007v + 0.0009v^2 - 0.00009v^3 \quad [0 \leq v \leq 11.2 m/s] \tag{22}$$

and

$$E(CO)_c = 0.0022 - 0.0002v + 0.000005v^2 \quad [v > 11.2 m/s] \tag{23}$$

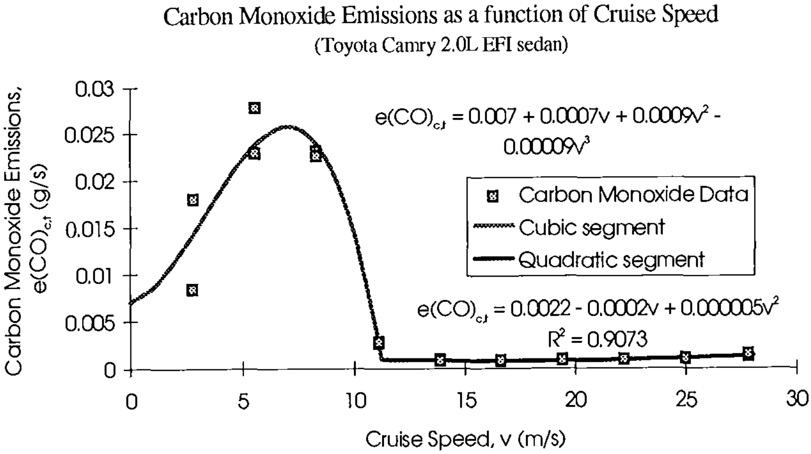

Figure 4 **Cruise carbon monoxide emissions as a function of cruise speed**

The cubic and quadratic curves intersect at a speed of v = 11.2 m/s and hence equation (22) should be applied for speeds up to and equal to 11.2 m/s and equation (23) should be used beyond this. The two curve segments described by equations (22) and (23) 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.

Acceleration phase models

Emissions data were also collected for acceleration and deceleration phases, namely accelerations from rest to 100 km/h and decelerations from 100 km/h to rest, at a range of acceleration/deceleration rates. The acceleration rates used were 2 km/h/s to 6 km/h/s, in increments of 1 km/h/s; the deceleration rates also included a rate of 8 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:

$$F_a = Av_f + Bv_f^2 \tag{24}$$

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 (eg 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. 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.

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

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

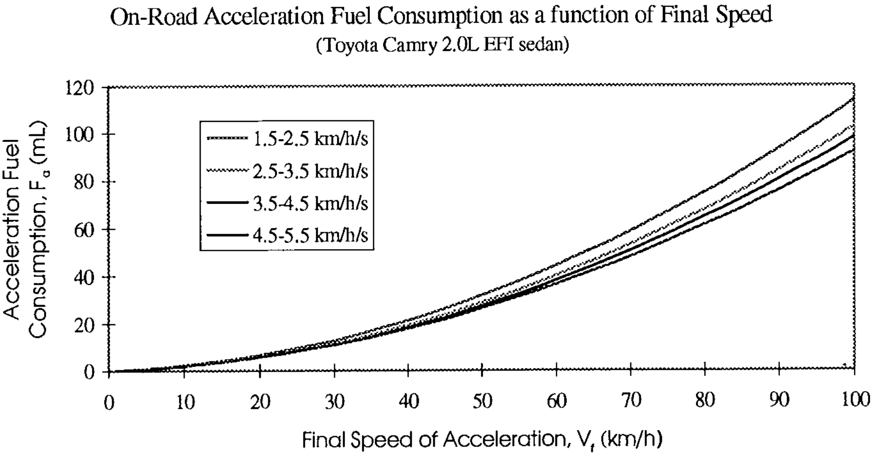

Figure 5 Acceleration fuel consumption, final speed of acceleration and acceleration rate (on-road data)

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 (ie 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.

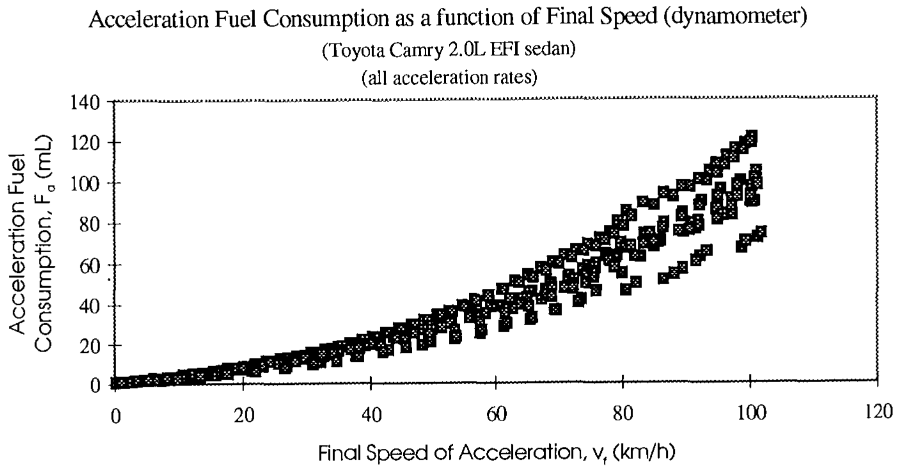

Figure 6 **Acceleration fuel consumption data and final speed of acceleration (dynamometer data)**

Table 3 **Model coefficients for dynamometer acceleration fuel consumption functions (Figure 7)**

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

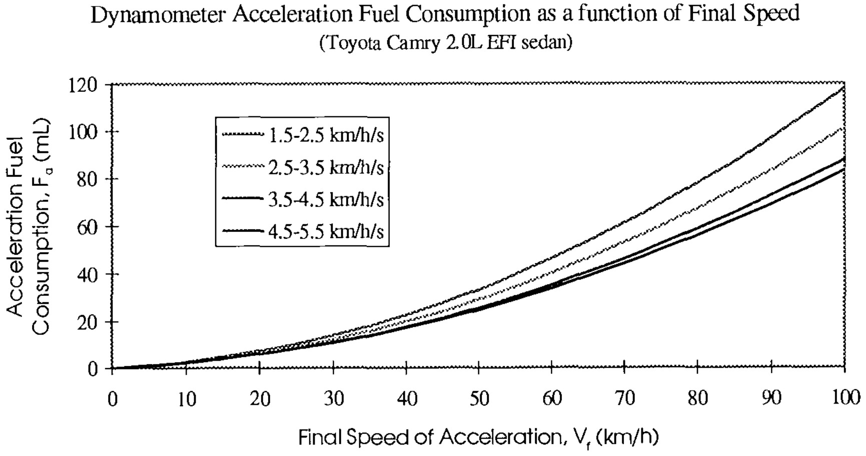

Figure 7 **Acceleration fuel consumption, final speed and acceleration rate (dynamometer data)**

The form of the fuel consumption function for acceleration phases, as in equation (24), was also found to be ideal for modelling acceleration carbon dioxide emissions, $E(CO_2)_a$.

$$E(CO_2)_a = Av_f + Bv_f^2 \tag{25}$$

where $E(CO_2)_a$ 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.

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

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

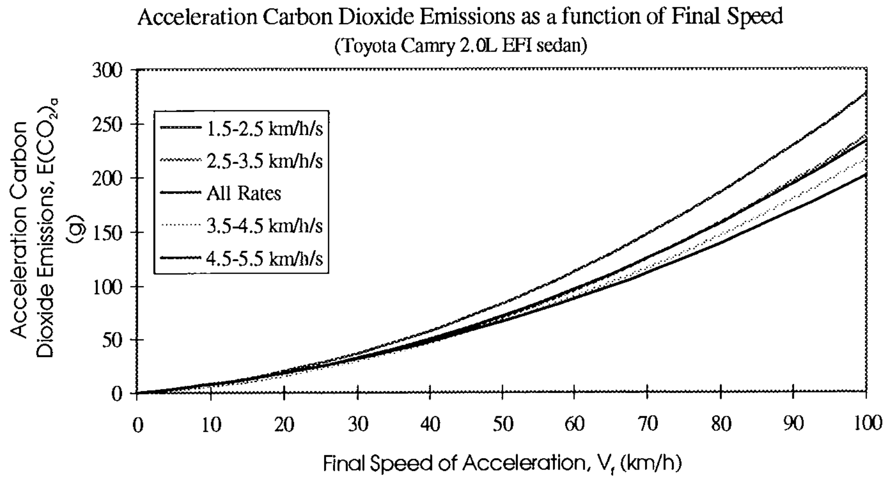

Figure 8 Acceleration carbon dioxide emissions, final speed of acceleration and acceleration rate

The form of function that was found to best describe the acceleration carbon monoxide emissions, $E(CO)_a$ data was an exponential function of the form given by equation (26).

$$E(CO)_a = A\, e^{Bv_f} \tag{26}$$

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

Table 5 Model coefficients for acceleration carbon monoxide emissions functions (Figure 9)

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

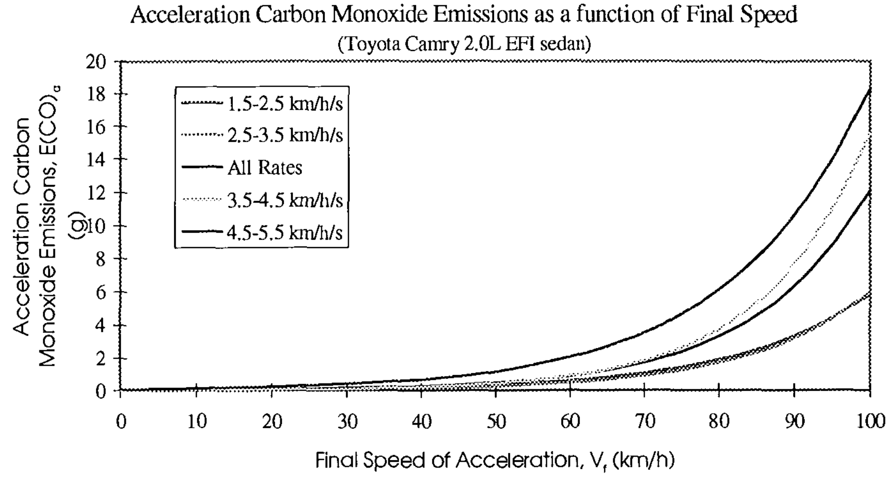

Figure 9 Acceleration carbon monoxide emissions, final speed of acceleration and acceleration rate

Further experimental work

The controlled tests on the dynamometer also included deceleration phases from 100 km/h to rest at a range of deceleration rates. Similar models (as functions of initial speed of deceleration, v_i) are being developed with the data obtained from these tests. Deceleration fuel consumption models are also being developed for the on-road data collected with the Toyota Camry instrumented vehicle.

A second instrumented passenger car, a Ford Falcon station wagon with a cylinder 4.0 L EFI engine is presently being tested, and tests on diesel-powered commercial vehicles and buses are proposed.

CONCLUSIONS

This paper described a family of models for estimating fuel consumption and pollutant emissions by vehicles in a traffic stream. The family of 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 paper also presented the first results of an experimental program aimed at providing a comprehensive set of vehicle, fuel and emissions parameters to aid the application of the models.

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