Modelling Environmental Impacts of Road Traffic for Transport Network Analysis

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Abstract:

Environmental and energy impacts are two important issues influenced by the performance of urban transport systems. This paper considers the development of a method to assess the impacts of transport systems and to ameliorate adverse environmental impacts over a study area. This includes the notion that it is not sufficient to model the amounts of pollution being generated. Considerations must also be made of the pollution loads actually impinging on land uses and populations in the study region. The modelling system draws on methods for transport network analysis and for fuel consumption and emissions modelling of individual vehicles. The paper indicates how these are being included in an environmental impact assessment package.

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The transport planning process has evolved considerable sophistication involving modelling of existing land use, road network and travel patterns, and forward projection using these models to predict future travel demand and road network needs. Transport demand modelling of this type is in regular use at the regional, urban and local area scales of transport planning and the modelling procedures have now devolved to readily available and widely used packages on personal computers.

However, the development of these transport demand modelling procedures has not kept pace with changing community demands, which now focus significant attention on travel demand management (TDM) and require the inclusion of environmental factors in the planning, design and implementation of transport infrastructure. Traffic on roadways is a significant cause of environmental degradation in urban areas, contributing to air pollution and noise, as well as causing problems of congestion, safety and intrusion. Current practice for dealing with these environmental matters usually involves an environmental impact assessment for planned works projects. While these impact assessment procedures are important, and will remain so, particularly in providing ameliorative measures for the worst environmental consequences of any project, their current weakness is that they come too late in the planning process - the important route location decisions have been made many years previously through travel demand modelling.

Recent research by Brown and Patterson (1990) introduced a novel approach to the assessment of the impacts of traffic noise, as an indication of the possibilities for a range of traffic-generated pollutants. They demonstrated that the noise impact of a planned road network could be explicitly included in travel demand modelling and network planning, i.e. when the network is still being developed, modelled and tested, rather than after the preferred route or potential alternative routes have been selected. In this regard the modelling work of Taylor and Anderson (1982, 1984, 1986, 1988) on estimating pollutant emissions from traffic streams is important, for this research focussed on the extension of traffic network models to provide information on emissions and to model the relationships between levels of traffic congestion, fuel consumption and pollutant emissions.

This paper considers the development of a computer-based method to assess the impacts of transport systems and to ameliorate adverse environmental impacts over a study area. It formulates a combined traffic assignment-trip distribution model for use at the strategic network level which is sensitive to alternative transport policy measures (e.g. in TDM), and which includes submodels for predicting fuel consumption and emissions. It indicates how these are being included in an environmental impact assessment package for application in traffic planning. This environmental impact assessment package consists of a set of PC-based computer models, linked through a common data structure, and making extensive use of interactive graphics displays.

Environmental and energy impacts represent two important community concerns influenced by the performance of road traffic systems. Fuel conservation and environmental degradation are of special importance (Jost, Ullrich and Waldeyer, 1987). Particular concerns have arisen with respect to:

(a)   fuel consumption, and the means for conserving liquid fuels;

(b)   air pollution, especially the emissions of gases and particulates from motor vehicles; and

(c)   noise, vibration and visual intrusion

Estimating the environmental impacts of road traffic

One procedural difficulty that has dogged planners and engineers has been how to assess the relative effects, merits and disadvantages of alternative transport infrastructure proposals at the planning stage. Survey methods for assessing levels of pollution are available for the study of existing conditions [e.g. Taylor and Young (1988); Maccarrone (1989)]. These methods cannot be applied to proposed developments, and alternative means for the appraisal of alternatives are required.

This issue was addressed in the 1970s by Wigan (1976), who provided the following methodology for predicting the environmental impacts of road traffic:
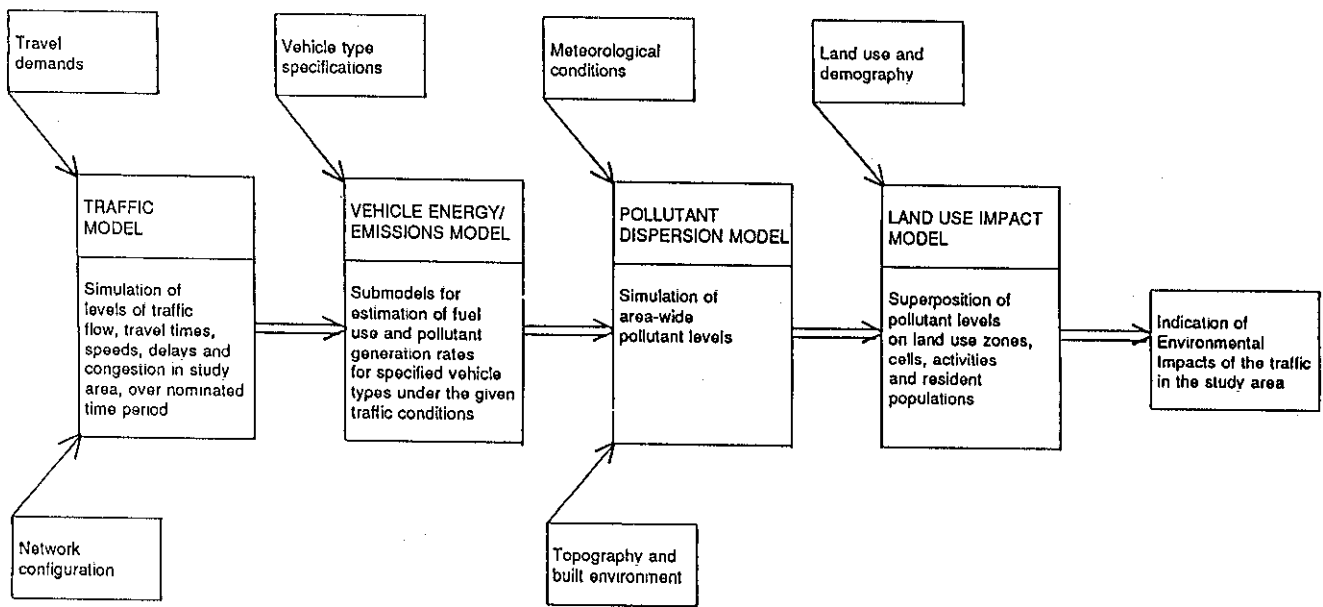
(1)   collate data on a link-by-link basis on road type, width, number of households, amount of activity by category of land use, etc;

(2)   obtain traffic flow data, including traffic composition and travel time, speed and delay;

(3)   develop a database that can provide the required link-by-link data to apply models of fuel consumption, emissions and pollutant dispersion;

(4)   apply a framework that defines the conditions under which the consumption, emissions and dispersion models can be applied;

(5)   generate indices of pollutant loads and environmental impacts (e.g. number of households subjected to a given noise level over a specified time interval);

(6)   prepare tabular and graphical representations of this information as histograms, pollution load maps, etc, and

(7)   indicate levels of individual and community annoyance under different pollution loadings.

Given the logical, 'common-sense' nature of this methodology, it may come as something of a surprise to realise that it has seldom, if ever been fully applied in practice! All too often transport planners and engineers have considered only the generation of pollution at its sources, not where that pollution will end up and who will be affected by it. The package described here follows Wigan's methodology through the construction of a combined model system, comprising a traffic network model, an emissions and fuel consumption model (or family of models), a pollution dispersion model, and a land use impact model. The research project for the development and integration of these separate functional models is a collaborative research project between the University of South Australia (U-SA), Griffith University and CSIRO, with financial support from ARRB, ARC, SENRAC and the U-SA/CSIRO collaborative research fund.

The basic scheme of the system is given 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

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Schematic modelling system for assessing environmental impacts of road traffic

Figure 1

Travel demands

Vehicle type specifications

Meteorological conditions

Land use and demography

TRAFFIC MODEL

Simulation of levels of traffic flow, travel times, speeds, delays and congestion in study area, over nominated time period

VEHICLE ENERGY/ EMISSIONS MODEL

Submodels for estimation of fuel use and pollutant generation rates for specified vehicle types under the given traffic conditions

POLLUTANT DISPERSION MODEL

Simulation of area-wide pollutant levels

LAND USE IMPACT MODEL

Superposition of pollutant levels on land use zones, cells, activities and resident populations

Indication of Environmental Impacts of the traffic in the study area

Network configuration

Topography and built environment

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 application of the modelling system of Figure 1 to predictions of environmental impact and energy use depends on the accuracy of the traffic model in reproducing travel conditions on the network, and the validity of the vehicle performance models. The application to environmental impact analysis is based on the premise that, although the actual absolute levels of pollution may be affected by many other factors besides those included in the component models, the modelling system can reasonably detect relative differences in levels of pollution between alternative sets of traffic load distributions (e.g. under alternative transport systems management plans or alternative travel demand management schemes).

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

Fuel consumption and emissions of road traffic

To gain an insight into the methods for assessing the severity of possible pollution problems, we must first consider the different fuels used in road transport, the range of pollutants generated by road traffic, the indications of environmental problems from these pollutants, and the mechanisms by which a community recognises the existence of problems of environmental degradation.

Road transport fuels

Virtually all of the road vehicle fleet is powered by petroleum-based liquid fuels. In Australia, the principal fuel is petrol, with some use of diesel fuel and liquid petroleum gas (LPG). Unleaded petrol (ULP) is the other major liquid fuel, of growing importance as the proportion of the vehicle fleet using ULP increases. This fuel was introduced in Australia in 1985, and all Australian petrol-driven passenger cars manufactured after March 1986 must run on this fuel. Table I indicates recent levels of consumption of the different fuels.

Super-grade (98 octane) petrol remains the most commonly used fuel for private passenger vehicles. Its use leads to emissions of the pollutants carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x) and particulate lead, besides emissions of water vapour and carbon dioxide. Diesel fuel is widely used for large vehicles, and occasionally by passenger cars. Diesel engines offer greater fuel efficiency

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Table 1   **Aggregate road transport and fuel consumption statistics for Australia, 1988 [source: ABS (1989)]**

Vehicle Type	Number of Vehicles (millions)	Annual Mean VKT (1000s km)	Fuel Usage (MegaLitres)			
			Leaded Petrol	Unleaded Petrol	Diesel	LPG
Cars and station wagons	7.286	15.8	10 216.4	2829.2	243.0	464.3
Motorcycles	0.291	6.7	97.5	18.3	-	-
Utilities and panel vans	1.163	18.7	1926.5	394.5	504.4	90.0
Rigid trucks	0.399	19.4	444.7	46.3	1459.8	70.2
Articulated trucks	0.048	78.7	4.4	1.4	2040.2	6.7
Other truck types	0.023	11.3	32.4	4.0	30.2	6.1
Buses	0.040	35.4	33.5	10.8	377.5	1.9
Totals	9.250	16.5	12 755.1	3304.6	4655.1	639.3

(more kilometres travelled per litre) and significant reductions in emissions of carbon monoxide (Taylor and Anderson, 1982). On the other hand, they may produce more VOC, as well as sulphur oxides (which are largely absent from petrol engine emissions). Diesel fuel may also produce more carbon dioxide per litre of fuel used (Young, 1992). LPG offers a cheap alternative to petrol for some vehicles. Vehicles powered by LPG are marginally less polluting than equivalent vehicles using super-grade petrol (Taylor and Anderson, 1982).

Pollutants from road traffic

Air pollution in urban areas typically consists of primary emissions such as carbon monoxide, volatile organic compounds (hydrocarbons), oxides of nitrogen and oxides of sulphur, and fine particulates (such as dust, soot and lead). In addition, carbon dioxide is also produced in quantity, although this has not been commonly regarded as a

pollutant (as it is an important natural component of the atmosphere). Current concerns about emissions of greenhouse gases require that emissions of carbon dioxide should be included in any environmental impact assessment involving gaseous emissions. Urban road traffic is a significant source of such pollutants. Derived pollution such as photochemical smog results from the chemical reaction of some of the primary pollutants (e.g. the VOC and nitrogen oxides) under conducive atmospheric and meteorological conditions. Indications of the magnitude of environmental problems facing metropolitan areas were given in Taylor (1990), based on studies by the Environment Protection Authority of Victoria (EPAV, 1979) for metropolitan Melbourne, and by Jost, Ullrich and Waldeyer (1987) (for western Germany). An update of the pollutant loads for metropolitan Melbourne in 1990 is now available (EPAV, 1991).

Studies in the UK [e.g. Hothershall and Salter (1977)] and elsewhere [e.g. OECD (1980)] indicate that road traffic is the single most important source of noise pollution in urban areas. Hothershall and Salter found that traffic was the primary source of noise pollution at more that 60 per cent of the sites they investigated.

An important consideration for transport planning is the extent to which traffic systems operations and traffic congestion contribute to pollution loads and energy consumption. Thus there is a need to establish methods and relationships that link traffic movements and travel conditions to the environmental and energy variables. This question is addressed in the latter half of this paper. Following the ideas of Wigan (1976) and Brown and Patterson (1990), it is essential that attention be given to the effects of the traffic-generated pollution on community groups and land uses. For this important reason a consideration of the development and recognition of pollution problems in a community must precede detailed study of the generation of pollutants from traffic sources.

Community-based pollution problems

Pollution problems occur at two distinct levels. In extreme cases the pollutant may offer a danger to the health and well-being of the individuals subjected to it. Excessive noise or excessive concentrations of air pollutants, such as carbon monoxide, may inflict immediate damage. Prolonged exposure to lower levels of various pollutants may lead to harmful effects for some individuals. The main pollution problems, however, are experienced at concentrations well below those injurious to health. These problems are those of annoyance, discomfort and anxiety in the face of pollution. Consequently most remedial treatments aimed at alleviating pollution problems are intended to overcome problems of annoyance: noise barriers along freeways would be a good example.

A generalised conceptual model of the process of pollution-generated annoyance is given in Figure 2, which is derived from the noise annoyance model described by Brown and Law (1976). Pollutants from one or more sources are dispersed towards a community, which may be at some distance from the source(s). The level of pollution arriving at the receptor location is influenced by a series of physical factors, including the original level of emission at the source, the separation of the source and receptor

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POLLUTANT   INTERVENING VARIABLES

Traffic flow, speed, composition
Other sources
Other pollutants
Attenuation effects of distance, vegetation, buildings
Time of day, week
Meteorological conditions

Individual susceptibility
Individual sensitivity
Acclimatisation
Attitudes to pollutant service
Attitudes to community
Aspirations

Socio-demographic factors

Pollutant Source

PHYSICAL FACTORS

HUMAN FACTORS

ANNOYANCE

COMPLAINTS

OTHER EFFECTS

Physical variables altered

Visitors Stimulate awareness to pollution

Interference with living habits and life style
Illness
Effect on property values
Move away because of pollutant
Anxiety
Insulate building
Alter building
Relocate activities in building.

EFFECTS OF POLLUTANT

Figure 2

Conceptual model of community/individual perception of a pollution problem, adapted from the noise annoyance model of Brown and Law (1976)
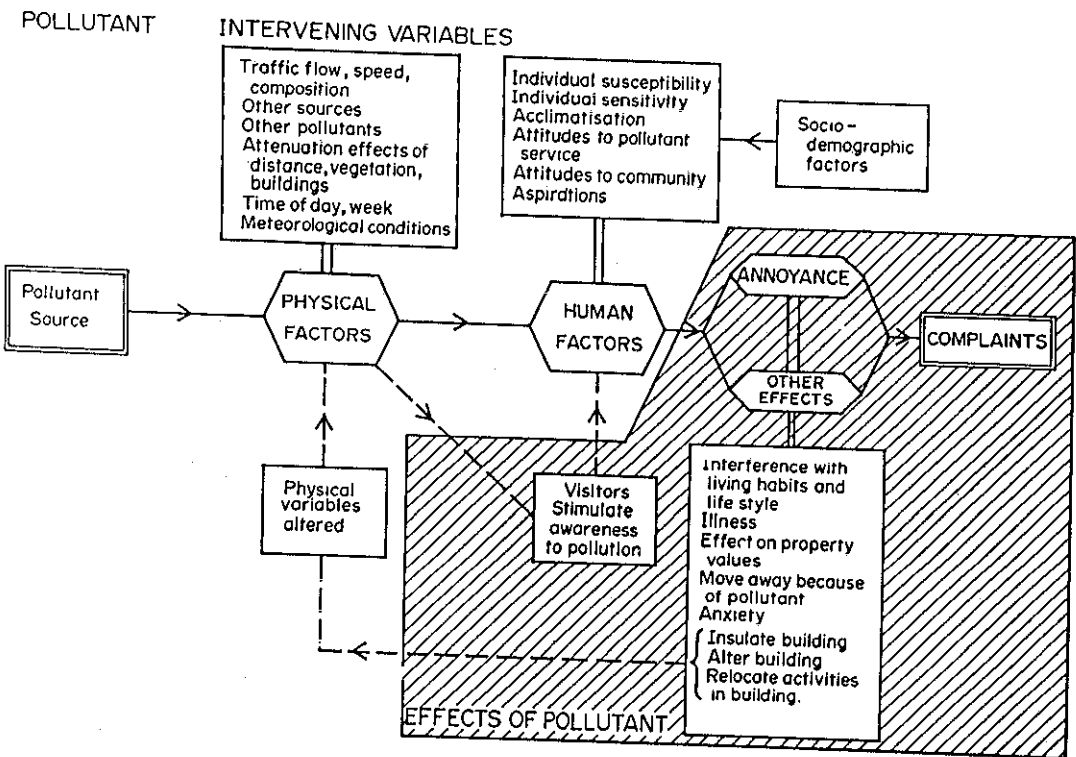
points, the local topography, climatic conditions, vegetation, and built environment. The CORTN noise level prediction model [UK DoE (1975); Samuels and Saunders (1982)] provides a useful example of this physical process.

How the pollutant is seen at the receptor point depends on the characteristics of the individuals and the attitudes of the community at that point. Typically, pollutant levels grow incrementally, so an individual may not notice the creeping effects Individuals may, however, be made aware of the pollution by the arrival of visitors who remark about the conditions, or by other means that lead to the increased sensitivity of the individuals to the pollution Expressions of anxiety and annoyance may then follow. One outlet for these feelings is complaints to the generators of the pollution, or to the authorities that regulate the activities of the polluters. Another outlet is that the individuals attempt their own remedial actions, such as reorganising the living activities and spaces of their household, refurbishing buildings (e.g insulation or double glazing to reduce internal noise levels), or by moving away from the area.

The conceptual model of Figure 2 presents the sequence of steps and feedback loops that lead a community or individual to recognise or perceive a pollution problem affecting them. It suggests the existence of threshold values, below which problems with a particular pollutant may not be seen. Further, it indicates that thresholds are dynamic, and may be altered (up or down) as a result of changes in community attitudes, available information and economic conditions

Predicting environmental impacts from road transport networks

The environmental impacts modelling system of Figure 1 provides a means for estimating the area-wide dispersion of pollution from a road network Previous applications of this modelling framework have focussed on local area studies, e.g Taylor and Anderson (1988) The framework may also be applied at the strategic network level, and an initial application of this kind was reported by Taylor and Anderson (1984). For application of the general system of Figure 1, the necessary information to be supplied or generated 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

Congestion models

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

$$
c = \begin{cases} c_0 \left\{ 1 + J \dfrac{\mu}{1 - \mu} \right\} & \mu < \rho \\[2em] c_0 \left\{ 1 + J \dfrac{\rho}{1 - \rho} + \dfrac{J}{(1 - \rho)^2}(\mu - \rho) \right\} & \mu \geq \rho \end{cases} \tag{1}
$$

where c is the link travel time, c_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 internal 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 [see Taylor (1984)]. This function provides 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 the subject of the latter part of this paper.

Segmentation of vehicle flows

Changing fleet composition and the contributions of different vehicle types and trip classes to fuel usage and pollution are important in TDM, e.g. to see how such changes might affect pollution levels. (The differences in energy and environmental performance between pre-1986 and post-1986 Australian vehicles 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

$$
q(e) = \sum_k q_k(e) \tag{2}
$$

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 (3). 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 equation (4).

$$
q_m(e) = \sum_k p_{km} q_k(e) \tag{3}
$$

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$$TE_a(X) \quad - \quad \sum_{km} E_m(X)\, p_{km}\, q_k(e) \tag{4}$$

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.

The basic form of such models is known, but only limited data (for a restricted number of vehicle types) is currently available. The U-SA/CSIRO/Griffith University collaborative research project aims to enlarge the database of available vehicle types.

Emission/consumption models for traffic streams

Four levels of fuel consumption and emissions modelling were proposed by Biggs and Akcelik (1986). Their 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 running speed model is suitable for application in strategic networks, for it can be used at the network link level.

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.

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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

$$\frac{dE(X)}{dt} = \alpha + \beta_1 R_T v + \left[\frac{\beta_2 M a^2 v}{1000} \right]_{a>0} \qquad \text{for } R_T > 0 \tag{5}$$

$$= \alpha \qquad \text{for } R_T \leq 0$$

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

$$R_T = b_1 + b_2 v^2 + \frac{Ma}{1000} + g \times 10^{-5} MG \tag{6}$$

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 these 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. Its accuracy for emissions modelling remains to be established but a similar level could be expected. 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.

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 c_i (seconds) over the route section. The vehicle is then assumed to travel at a constant running speed v_r (km/h), where

$$v_r = \frac{3600x_s}{c_s - c_i} \tag{7}$$

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

$$E_s = \max\left\{ f_r + \frac{\alpha t_i}{x_s}, \frac{\alpha t_i}{x_s} \right\} \tag{8}$$

where

$f_r \quad = \quad$ 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

$$f_r = \frac{3600\alpha}{v_r} + A + Bv_r^2 + k_{E1}\beta_1 + ME_{k+} + k_{E2}\beta_2 ME_{k+}^2 + g k_G \beta_1 M \frac{G}{100} \tag{9}$$

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

$$E_{k+} = \max\{0.35 - 0.0025v_r, 0.5\} \tag{10}$$

as described by Bowyer, Akcelik and Biggs (1985). The calibration parameters k_{E1}, k_{E2} and k_G may be estimated from

$$k_{E1} = \max\left\{ 0.675 - \frac{1.22}{v_r}, 0.5 \right\} \tag{11}$$

$$k_{E2} = 2.78 + 0.0178v_r \tag{12}$$

$$k_G \quad \begin{array}{ll} = 1 - 1.33E_{k+} & \text{for } G < 0 \\ = 0.9 & \text{for } G > 0 \end{array} \tag{13}$$

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 (from Bowyer, Akcelik and Biggs, 1985) an estimate of the running speed v_r (km/h) may be made from equation (14), given knowledge of the overall average link travel speed v_s (km/h).

$$v_r \;-\; \max\left\{8.1 \;+\; 1.14v_s \;-\; 0.00274v_s^2, \; v_s\right\} \tag{14}$$

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. 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 remains to be determined.

A fuel/emissions model for transport network analysis

A combination of the congestion function defined in equation (1) and the E/C running speed model defined by equation (8) may then be used to estimate the E/C rate for a link of a given type operating at a given volume-capacity ratio. This combined model can then be included in a transport network model (e.g. for traffic assignment or for combined distribution and assignment). Tables 2 and 3 provide the necessary parameter values for the generation of specific E/C functions for the average pre-1986 Australian car for different road types in terms of one-way link volume/capacity ratios. Figures 3-6 show functions for fuel consumption and emissions of carbon monoxide, carbon dioxide and VOC, for dual carriageway arterial roads in inner, middle and outer metropolitan locations. A value of $\rho = 0.9$ was used to generate these relationships.

Applications in transport network planning

Two conceptual models of traffic assignment that are responsive to volume/capacity ratios were given by Wardrop (1952). Wardrop's principles are:

(1)   drivers could select routes that minimises their own individual travel times, on the basis that all other drivers are making their own individual decisions and that these decisions are made independently. Under the resulting flow patterns, all of the alternative routes used for a specified journey will have equal travel times, and these travel times will be less than those on any other possible route for that trip. The resulting flow pattern is stable, for no one driver can change route and gain any advantage by doing so. The resulting model is the 'individual travel time minimisation model'. This model provides a realistic simulation of present-day driver route choice behaviour. Alternatively,

(2)   drivers could select routes so that the overall amount of travel (vehicle-hours of travel) in the network is minimised. This principle requires complete cooperation and sharing of information between drivers. It leads to a 'system travel time minimisation model' flow pattern with the minimum amount of total travel for

Table 2 **Davidson function parameters (after Taylor (1984))**

Link Description		Davidson Parameters		
Road Type	Area	S (veh/h/lane)	J	c_0 (min/km)
Undivided, multilane	Inner	1344	0.475	1.15
Undivided, multilane	Middle	1675	0.468	0.85
Undivided, multilane	Outer	1741	0.486	0.80
Undivided, with LRT		1317	0.350	1.15
Divided	Inner	1607	0.374	1.06
Divided	Middle	1861	0.415	0.83
Divided	Outer	1911	0.419	0.79
Freeway		3055	0.138	0.70

Table 3 **Emission and fuel consumption parameters for pre-1986 average car (after Bowyer, Akcelik and Biggs (1985) and Akcelik (1990))**

Parameter	Fuel	VOC	Carbon Monoxide	Nitrogen Oxides	Carbon Dioxide
α (seconds^{-1})	0.444	0.0022	0.0139	0.0006	1.0212
β_1	0.090	0	0.015	0.001	0.207
β_2	0.0450	0.0040	0.0250	0.0002	0.1035
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

Figure 3

Derived link function for fuel consumption (pre-1986 average car)

Pre-1986 Average Car : Dual Carriageway Arterial
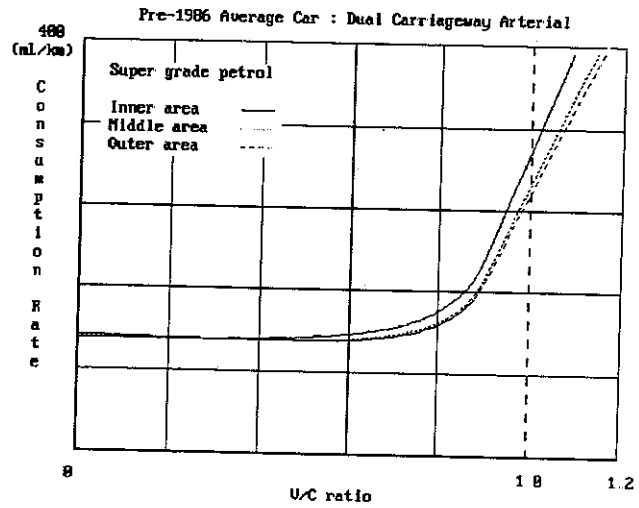
Figure 4

Derived link function for emissions of carbon monoxide (pre-1986 average car)

Pre-1986 Average Car : Dual Carriageway Arterial

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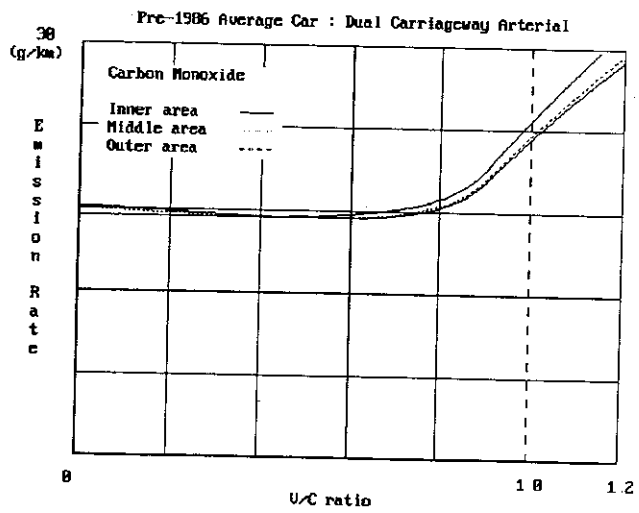
Figure 5

Derived link function for emissions of carbon dioxide (pre-1986 average car)

Pre-1986 Average Car : Dual Carriageway Arterial
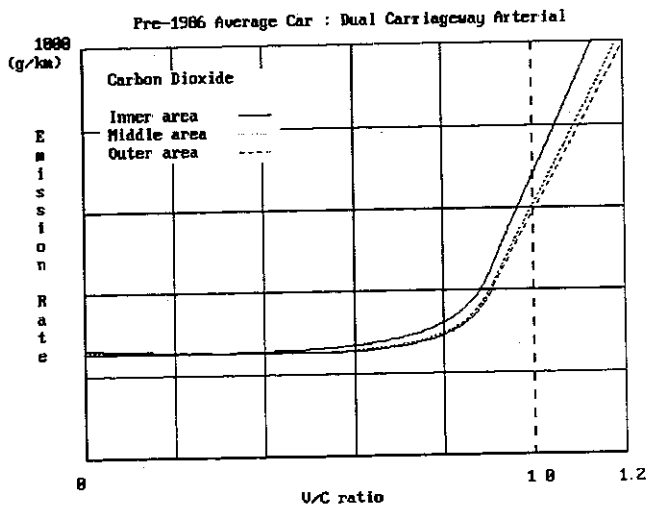
Figure 6

Derived link function for emissions of VOC (pre-1986 average car)

Pre-1986 Average Car : Dual Carriageway Arterial
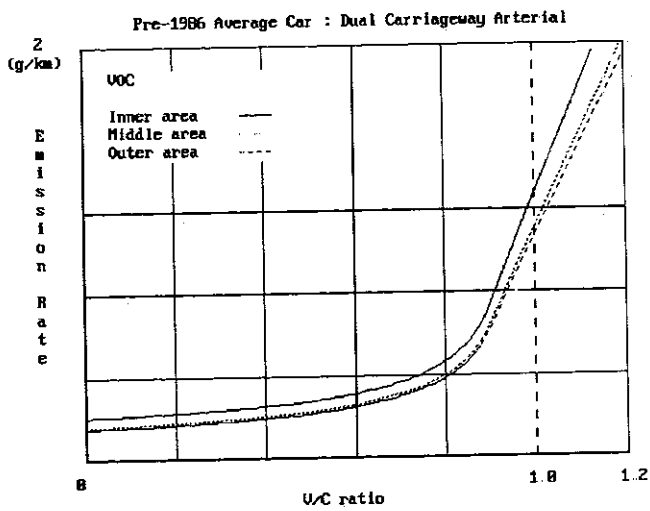
the supplied (fixed) travel demand, but this flow pattern is unstable as individual drivers may find alternative routes that offer them quicker individual travel times.

These conceptual models may be stated in mathematical form as follows. The equilibrium assignment model for fixed (inelastic) travel demand is an expression of Wardrop's first principle (individual travel time minimisation). This model formulation provides a useful macroscopic simulation of travel on a metropolitan network. It may be written as the following non-linear optimisation problem, for which a convergent solution may be found (as indicated, for example, in Taylor (1984)):

$$Z \; - \; \min \left\{ \sum_e \int_0^{q(e)} c_e(x) dx \right\} \tag{15}$$

subject to the continuity of flow constraints

$$T_{ij} \; - \; \sum_r X_{rij} \qquad \forall \; i, j \tag{16}$$

and

$$q(e) \; - \; \sum_{ijr} \delta_{eijr} X_{rij} \qquad \forall \; i, j \tag{17}$$

where

$$\delta_{eijr} \quad = \quad 1 \qquad \textit{if and only if } e \text{ is in path } r \text{ from i to j,}$$
$$= \quad 0 \qquad \text{otherwise}$$

X_{rij} is the number of trips using path r between i and j, and the function $c_e(q)$ is the congestion function for link e.

The equivalent system-wide travel time minimisation problem may be written as a similar optimisation problem, with objective function

$$Z \; - \; \min \left\{ \sum_e q(e) \, c_e(q(e)) \right\} \tag{18}$$

with the same conservation of flow constraints

Given the flow pattern corresponding to either of these traffic assignment models, the total fuel consumption and emissions generated can be estimated using the link E/C relationships described in the previous section.

The Wardrop principles may be treated as meeting different economic objectives for network travel, if travel time is taken as one possible alternative measure of travel cost. Jewell (1967) expanded this argument by suggesting a third principle for traffic assignment: that the ultimate pattern of flow in a network will satisfy some explicit economic objective, for instance minimum generalised travel cost or minimum fuel consumption (both either individual or system-wide). Thus direct substitution of the link

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E/C functions for the congestion function $c_e(q)$ would yield assignment models that could generate traffic patterns corresponding to minimum fuel use or minimum pollution generation. A generalised cost function including travel time, fuel consumption, pollutant emissions, money costs etc could also be proposed and solved.

Consideration of elastic travel demand

In the case that travel demand (as represented by the trip matrix T_{ij}) is regarded as elastic, i.e. the trip distribution (destination choice) will vary depending on the congestion levels in the network, then an alternative model formulation is in order. The combined distribution-assignment model proposed by Evans (1976) and explained by Horowitz (1989) provides an equivalent formulation to the equilibrium assignment model, and may be solved by a similar mathematical programming approach. On the assumption that the trip distribution can be explained by the entropy-maximising model

$$T_{ij} = r_i P_i s_j A_j \exp(-\lambda c_{ij}) \tag{19}$$

where P_i is the trip production of i, A_j is the trip attraction of j, c_{ij} is the travel cost between i and j and λ, r_i and s_j are calibration constants, then the elastic-demand traffic assignment model is

$$Z = \min\left\{\sum_e \int_0^{q(e)} c_e(x)dx + \frac{1}{\lambda}\sum_i \sum_j T_{ij}\left[\ln(T_{ij}) - 1\right]\right\} \tag{20}$$

subject to the constraint equations (16) and (17). This model may be treated in identical fashion to the equilibrium assignment model for fixed travel demand. It has considerable promise as a transport network model for use in analysis of TDM programs. With the addition of fuel and emissions relationships of the form discussed in this paper, it offers a useful means to examine the ways in which variations in vehicle fleet composition, travel demand patterns and congestion levels will influence energy consumption and pollution emissions from urban transport systems.

Conclusions

An elastic-demand transport network model of the type defined by equation (2) can be usefully employed within the general environmental impact assessment framework of Figure 1, given suitable functions that relate emissions and energy consumption of link traffic streams to link volumes. This paper has discussed how such functions may be generated, and has provided some examples. There are a number of research and development tasks to be finished, e.g. the development of link-based emissions and energy functions for a range of vehicle types (including post-1986 passenger cars, trucks and buses), and considerations of alternative definitions of travel

costs to include a set of congestion, energy and environmental variables. The outcome of this research will be a strategic transport network model that may be applied to questions involving considerations of Travel Demand Management. As such, it may point the way to some new policy-sensitive and relevant transport models.

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