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A "Stable" of Traffic Network Equilibria and its Use in Analysing the Impacts of Transport Policies

Michael Taylor
University of South Australia

Abstract

Traffic assignment models have a central place in transport planning, for they provide necessary information on the traffic and congestion loads to be borne across a network and how those loads may vary depending on network configuration, design standard, control regime and travel demand distribution. This paper focuses on static equilibrium assignment models because of their relevance in transport policy analysis, that is as models of congested traffic networks that may be used to examine the effects of policy alternatives in environmental and energy management, travel demand management (TDM), traffic calming, congestion management and road pricing, and land use-transport interactions. To make static assignment models really useful for these broader level policy analyses requires more flexible definition of the assignment models, and it is this broader definition that is the principal aim of this paper.

The paper describes a set of equilibrium assignment models with separate objective functions for travel time, generalised travel costs and a set of road pricing regimes, which are linked by a common model structure. The models include elastic travel demands and trip timing analysis, and in this way enable the study of alternative network configurations, travel demand management policies, and (potentially) population and land use distributions. They enable comparisons of different policies to be made on a common basis. The paper pays particular attention to the effects of network congestion and the possible effects of road pricing in central city areas. Two case studies are examined: Adelaide and Melbourne.

Contact Author

Michael Taylor
Transport Systems Centre
University of South Australia
GPO Box 2471
Adelaide SA 5001

Phone: +61 8 8302 1861 Fax: +61 8 8302 1880 e-mail: MAP.Taylor@UniSA.edu.au

Introduction

The potential of equilibrium traffic assignment models in transport planning and policy analysis has never quite been fully appreciated. Although reliable and theoretically sound solution procedures for equilibrium assignment have been available for at least twenty years, the model has not found a regular place in the state of practice. Perhaps its full capability and qualities have not been obvious to practitioners? While some researchers continue to develop and extend equilibrium-based assignment tools (e.g. Tatineni, Lupa, Englund and Boyce, 1995; Bell and Iida, 1997) others stress the needs to develop dynamic assignment models (e.g. Ran, Lo and Boyce, 1996). Consideration of equilibrium assignment as providing a related set of models with a common conceptual basis and consistent assumptions (collectively, a 'stable' of equilibrium solutions) provides a useful tool for comparing the impacts of different transport and environmental policies. This paper develops and applies a set of equilibrium assignment models of congested traffic networks that may be used in framing transport policies for environmental and energy management, travel demand management, traffic calming, congestion management, road pricing, and land use-transport interactions. Its focus is on a comparison of alternative road pricing regimes for urban areas.

The general user equilibrium traffic assignment model for a given travel demand defined by the origin-destination matrix $\{T_{ij}\}$ of trips between origins i and destinations j is given by the mathematical programming problem

$$Z_U = \min\left\{\sum_e \int_0^{q(e)} g_A(e,x)dx\right\} \quad (1)$$

such that

$$T_{ij} = \sum_r X_{rij} \qquad \forall \quad i,j \quad (2)$$

$$q(e) = \sum_{ijr} \delta_{eijr} X_{rij} \qquad \forall \quad e \quad (3)$$

$$q(e) \geq 0 \qquad \forall \quad e \quad (4)$$

and

$$X_{rij} \geq 0 \qquad \forall \quad r, i, j \quad (5)$$

where $q(e)$ is the traffic volume on link e, X_{rij} is the number of trips using path r between i and j, $g_A(e, q)$ is the generalised travel cost on link e, and

$\delta_{eijr} = 1$ if and only if e is in path r for pair ij

$\delta_{eijr} = 0$ otherwise

The constraint equations (2)-(5) are based on continuity of flow conditions, and define a feasible solution for the network flows. Any set of link volumes satisfying these constraints is a feasible solution. Use of travel time as the representation of generalised cost leads to the user equilibrium model satisfying Wardrop's first principle (W-I).

Another solution is the system equilibrium solution minimum total vehicle-hours of travel (VHT) in the network, Wardrop's second principle (W-II). In broader terms, the objective function for the system optimum generalised cost is

$$Z_S = \min\left\{\sum_e g_A(e, q(e))q(e)\right\} \tag{6}$$

Traffic congestion

Traffic congestion presents a common if not inevitable facet of traffic activity in urban areas. The spread, duration and intensity of congestion, the processes that lead to it, and the consequences of it are of special concern in urban policy making and transport planning. Although congestion is an integral part of a transport system, its specific definition and identification are not immediately obvious. The following definition of congestion can be proposed for use:

> 'traffic congestion is the phenomenon of increased disruption of traffic movement on an element of the transport system, observed in terms of delays and queuing, that is generated by the interactions amongst the flow units in a traffic stream or in intersecting traffic streams The phenomenon is most visible when the level of demand for movement approaches or exceeds the present capacity of the element and the best indicator of the occurrence of congestion is the presence of queues'. (Taylor, 1998)

This definition recognises that the capacity of a traffic systems element may vary over time, e.g. when traffic incidents occur). Thus congestion may always be present in any part of a transport system, but that the level of congestion may have to exceed some threshold value to be recognised. The threshold may be context-specific, for instance owing to the occurrence of incidents such as breakdowns, road works, or road crashes.

For strategic transport planning purposes a satisfactory definition of the level of congestion on a network component (e.g. a route, link or intersection turning movement) is the excess travel time incurred by a traveller when traversing that network component. Excess travel time is the additional travel time over and above the free flow travel time (c_O), which is the minimum amount of time required to cover the element. Thus excess travel time corresponds to the 'system delay' under the given traffic conditions (Taylor, Young and Bonsall, 1996). Further, we assume that travellers may be able to trade-off excess travel time (or indeed total travel time) for other components of the overall cost of travel on a trip. This requires the concept of a generalised cost of travel for a trip. The economic basis for the trade-off is illustrated by the theory of road pricing (e.g. May, Milne, Smith, Ghali and Wisten, 1996),

Congestion functions

A congestion function describes the relationship between the amount of traffic using a network element and the travel time and delay incurred on that element. The total travel time to traverse a network element is directly related to the traffic volume using that element. As volume increases, so delay, and hence travel time, increases. The rate of increase in travel time accelerates as volume approaches the capacity of the element. For most transport planning applications the network link is the typical level at which congestion functions are applied, but for traffic engineering applications function for lanes and movements may be more appropriate. A convenient way to represent a congestion function is in terms of the travel time on a link, in which c is the travel time on the link when it is carrying traffic at a flow rate of q, and the function includes a set of parameters that describe the physical and environmental characteristics of the link and the sources of interference impinging on the flow (e.g. opposing traffic, or parked vehicles). One useful form for a congestion function is the modified Davidson function (Tisato, 1991):

$$c = c_0\left(1 + J\frac{x}{1-x}\right) \qquad x < x_0$$

$$c = c_0\left(1 + J\frac{x_0}{1-x_0} + J\frac{x - x_0}{(1-x_0)^2}\right) \qquad x \geq x_0 \tag{7}$$

where x is the 'volume-capacity ratio' (or 'degree of saturation'), J is an environmental parameter reflecting the physical form of the road and its abutting land use, and x_0 is a user-selected proportion, usually in the range (0.85, 0.95) as discussed by Taylor (1984).

Fuel and emissions functions for network elements

Taylor (1996) indicated how a congestion function could be combined with fuel consumption and pollutant emissions models to generate link-based fuel and emissions functions for use in transport network modelling, in which fuel usage and emissions are related to link volume-capacity ratios. Taylor (1998) provides examples of the use of the fuel and emissions functions.

Road pricing

Congestion provides a natural but partial restraining mechanism on travel demand. The additional costs (delays, queuing and inconvenience) resulting from congested conditions can act as a form of deterrent to the generation of further travel demand. However, there is widespread belief amongst transport planners that the congestion 'price' of itself is inefficient as a demand management tool. Individual drivers may not be fully aware of the true costs that they impose on other travellers and the transport system on the basis of congestion delays alone. Some other pricing signal is required to this end. Assuming that travellers will respond to a composite generalised cost (i.e. a total travel cost containing components from travel time, travel distance, out-of-pocket expenses, fuel cost, wear and tear, etc.) by trading-off the different cost components in their travel decision making, the further step is to impose a congestion tax, toll or road pricing charge on travellers in an intelligent, selective fashion (e.g. for travel on some parts of a network at some times of day)).

The economist's conceptual model for a congestion price is that of the demand-supply equilibrium and the relationship between the average travel cost on a link and the marginal cost. The average cost is less than or equal to the marginal cost for all positive link volumes. A congestion charge could be imposed on motorists to enable them to meet their full marginal costs, this means the imposition of a congestion charge ΔG on each vehicle. The marginal travel cost on a link is g_m where

$$g_m = \frac{\partial G_T}{\partial q} = \frac{\partial (g_A(q)q)}{\partial q} \tag{8}$$

and G_T is the total travel cost on the link In general $G_T = g_A q$, but in the case where travel time alone is take as the travel cost, i.e. $G_T = cq$, it can be shown that for the Davidson function *c(x)* defined by equation (7) the marginal cost is given by

$$g_m = c_0\left(1+\frac{2Jx}{(1-x)^2}-\frac{Jx^2}{(1-x)^2}\right)=c(x)+\frac{c_0 Jx}{(1-x)^2} \qquad x < x_0$$

$$g_m = c_0\left(1+\frac{2Jx_0}{(1-x_0)^2}-\frac{J(2x-x_0)}{(1-x_0)^2}\right)=c(x)+\frac{c_0 Jx}{(1-x_0)^2} \qquad x \geq x_0 \tag{9}$$

Equation (9) thus enables the 'congestion tax' or 'road price' (ΔG) to be identified explicitly, given that $g_m(x) = c(x) + \Delta G$

Use of marginal travel costs (e.g. equation (9)) rather than average travel costs (equation (7)) for all links in the network provides an appropriate network equilibrium model including individual choice in the presence of a perfect road pricing regime. Other cases of road pricing implementations may be more interesting? For example, what if the road pricing is only imposed on a subset of the links (e.g. in a downtown area or regional activity centre), and not across the whole network? In addition, there is the question of how a practical road pricing system might be implemented? Technological developments not withstanding, it seems unlikely that a perfect, real-time road pricing system, in which marginal costs are adjusted continuously in response to traffic flow variations, can be readily employed. Some simplified systems of imposing the 'congestion charge' ΔG are more likely to be used.

May *et al* (1996) described four alternatives for applying road pricing to real networks Collectively, these may be termed the 'Leeds models', and they are defined as:

1. road pricing based on charges for usage of road space, perhaps in a specified sub-area - the road pricing zone', which corresponds to the application of marginal travel costs on the road links in that area;
2. cordon based road pricing, in which drivers are charged for entering the road pricing zone. The congestion charge is thus a fee imposed for traversing the links that feed in to the road pricing zone;

3 travel distance-based road pricing, in which a per unit distance charge is levied on each vehicle travelling along the links in the road pricing zone, and
4 travel time-based road pricing, in which a per unit time charge is levied on each vehicle travelling along the links in the road pricing zone.

The first Leeds model considers marginal costs. Travel-time based road pricing is both practical and perhaps closest to marginal cost pricing but may be seen as inequitable? For instance, if drivers are delayed in the road pricing zone due to some traffic incident inside (or even outside) the zone which is beyond their control or influence, then the charge they incur may be unreasonable - an element of individual choice has been removed. There is also some evidence that drivers operating under this regime could engage in higher-risk driving behaviours (Bonsall and Palmer, 1997). Distance-based road pricing may be more equitable and can still account for different levels of travel activity in the zone. It is also easier to provide drivers with advance warning of the charges they will incur. This ease of advice is even more apparent for cordon-based pricing, but this system cannot differentiate between long and short journeys within the road pricing zone, nor for trips which are completely internal to it.

Equilibrium assignment models for road pricing

Equation (8) indicated the relationship between the marginal cost of travel and the average cost of travel on a link. Substitution of the marginal cost of travel in the objective function for the user-minimisation equilibrium assignment (equation (1)) shows that it is equivalent to solving the system-wide travel time optimisation problem (equation (6)) This is indicated below, starting with equation (10) which is the user equilibrium objective function based on marginal travel costs (equation (8)).

$$Z_{RP} = \min\left\{\sum_{e}\int_{0}^{q(e)} g_m(e,x)dx\right\} \tag{10}$$

Consider the integral in the right hand side of equation (10). Assuming that travel time represents the travel costs and using the definition of marginal travel cost in equation (8), this can be written as

$$\int_{0}^{q(e)} g_m(e,x)dx = \int_{0}^{q(e)} \frac{\partial(c_e(x)x)}{\partial x} = \left[c_e(x)x\right]_0^{q(e)} = c_e(q(e))q(e)$$

from which

$$Z_{RP} = \min\left\{\sum_{e}\int_{0}^{q(e)} g_m(e,x)dx\right\} = \min\left\{\sum_{e} c_e(q(e))q(e)\right\}$$

i.e. the full marginal cost road pricing objective is the system-wide minimum travel time (minimum VHT, see equation (6)), under the continuity of flow constraints (equations (2)-(5)). In the case where road pricing might only be applied to a subset of the roads (e.g. the central business district) whereas other links remained in their 'normal' state, then the road pricing solution is found by using a composite objective function (e.g. derived from equation (10) for a user equilibrium formulation). Different objective functions apply to 'Leeds models' as described by Taylor (1998).

The first Leeds road pricing model, that of charging for the use of road space in the road pricing zone, is based on the application of marginal costs to all links within that zone. The marginal cost functions apply to those links inside the road pricing cordon area and the average cost functions applies to all other links.

The second Leeds model is cordon-based road pricing, in which drivers are required to pay a fixed charge when they cross the cordon line to enter the road pricing zone. The corresponding objective function is the original user equilibrium objective function with an additional (money) cost on each link crossing the cordon line on entry to the road pricing zone.

The third Leeds model is that of travel distance-based road pricing. Each vehicle is charged for the distance travelled in the road pricing zone, and the objective function includes a money cost based on link length, for each link in the road pricing zone.

The final Leeds road pricing model is for time-based road pricing. Here each vehicle is charged a given amount for each unit of time that it spends in the road pricing zone. The corresponding objective function includes a money cost based on link travel time for each link in the road pricing zone.

Elastic travel demands

Elastic demand equilibrium assignment models are of growing relevance and importance (Hills, 1996). Two component forms may be considered: (1) time-elastic travel, where the total travel demand over an extended time period is fixed in space, and some drivers can choose their departure times in particular intervals within the overall time period; and (2) a long-run space-elastic model where travellers can set their origins and destinations in response to congestion on the network. This model has applications in land use-transport interaction studies. Models including time and space elasticity are also required.

Time-elastic travel demand

Traffic models accounting for trip timing and peak spreading behaviour are useful for studies of the impacts of travel demand management policies and time-dependent road pricing systems. Matsui and Fujita (1996) derived a model for individual travel time minimisation including departure time choice, which fits closely to the equilibrium assignment model family described previously. The model is based on the following assumptions:

(1) the total travel demand for a given period of time and represented by the O-D matrix $\{I_{ij}\}$ may be split into two components, a set of fixed-time O-D matrices $\{H_{ij}^{n}\}$ for travellers constrained to depart in a given time interval n, and a time-variable O-D matrix $\{F_{ij}\}$ representing travellers free to choose a departure interval, and

(2) those travellers able to select a departure interval have a probability P_n of choosing to depart in time interval n given by a multinomial logit model.

Matsui and Fujita applied the model to Toyota City, Japan, to study the impacts on congestion and journey times of a flexitime system and a road pricing system (in which a fixed charge was levied for travel on the entire network in one 60 minute period, 07:30-08:30, with no charge in other time intervals) They found a five per cent reduction in VHT under the flexitime regime, and a two per cent reduction under the road pricing system.

Space-elastic travel demand

In the case that travel demand is regarded as elastic, i.e. the trip distribution (destination choice) may 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 Such a model may be treated in identical fashion to the equilibrium assignment model for fixed travel demand More complex models including modal choice have also been developed, e.g. Tatineni *et al* (1995).

A demand elasticity approach to elastic travel demand modelling

With the growing interest in trip timing decisions, especially for peak spreading and travel demand management considerations, an obvious future step is the integration of the time-elastic and space-elastic models into a single elastic-demand model. There is also the question of the influences of levels of traffic congestion on the demand to use road space (i.e. on the total vehicle kilometres of travel (VKT)), which involves considerations of the phenomenon of 'induced traffic' (e.g. Hills, 1996) Elastic travel demand is of necessary concern in studies of road pricing. For instance, if road pricing is intended to provide motorists with better cost and impact information on which to base their travel choices, then it is to be expected that some travellers will decide to change their mode of travel, trip timing, or destination choice

A simple way to model these choices is through the use of demand elasticity as defined in the economic theory of supply and demand. This topic has the subject of some recent research in Australia, e.g. see Bray and Tisato (1997) and Taplin, Hensher and Smith (1999). A demand elasticity approach based on this research was adopted for use with the equilibrium assignment models for road pricing This enabled the origin-destination tables to be adjusted for each of the road pricing schemes.

In Australia, the cross-elasticity for travel by public transport is quite low. Taplin, Hensher and Smith (1999) derived a price elasticity of -0.094 for commuter car travel, when public transport is the only available alternative They suggested a total price elasticity of about -0.17 when alternatives such as change of trip timing and destination were included. On this basis, it was assumed that there were separate elasticity values: (1) e_m = -0.094 for shift to public transport, (2) e_t = (say) -0.04 for shift to other times of day, and (3) e_d = (say) -0.03 for shift to other destinations. Route deviation .

effects are included as part of the output of the assignment models for the different road pricing regimes. Although the Taplin *et al* elasticity values are expressly for Sydney, they have been used in the absence of similar data for other Australian cities.

The component elasticities needed be applied differently to different origin-destination combinations, depending on whether the trips lie wholly within the road pricing zone, or have one trip end in the zone, or are completely outside it. For example:

- e_m and e_t apply to all trips with an origin and/or a destination in the road pricing zone, while
- e_d only applies to all trips with an origin outside the road pricing zone and a destination within it, when there are alternative destinations available outside the zone (and so it might not apply if the road pricing system extends over the entire network, except to perhaps prefer closer destinations to those further away?)

This is better seen in terms of a schematic origin-destination table, with N origins and destinations of which the first n origins and destinations are located within the road pricing zone.

	Destinations 1 … n	n … N
Origins 1 … n	Origins and destinations inside the road pricing zone, e_m and e_t apply	Origins inside the road pricing zone, e_m and e_t apply
n … N	Destinations inside the road pricing zone, e_m, e_t and e_d apply	Origins and destinations outside the road pricing zone, no effect on time and mode choices, except that the destinations may gain trips via e_d (i e shift from destinations inside the road pricing zone to those outside)

The time horizon for the analysis is the short to medium scale, where commuters can change their trip making habits, and perhaps their destinations, but not (say) their place of residence, i.e. the time scale is such that no one has sold their house because of the road pricing zone!

Elasticity values may be applied in terms of the 'arc' elasticity of demand:

$$e = \frac{\Delta Trips / Trips}{\Delta Cost / Cost} \quad \text{which can be rewritten as:} \quad \frac{\Delta Trips}{Trips} = e \frac{\Delta Cost}{Cost} \qquad (11)$$

Average values of *Cost* and *ΔCost* were found by the following procedure. Find the total link costs of travel in the road pricing zone under the base condition (no road pricing used). The mean of these costs is C_0. Run the model with the road pricing regime in place, and using the original origin-destination table (i.e. fixed commuter car demand). Determine the new mean cost of travel in the road pricing zone (C_1). Then

$$Cost = C_0 \quad \text{and} \quad \Delta Cost = C_1 - C_0$$

Then use equation (11) to revise the trip productions and attractions of the affected origins and destinations (i.e. for those trips with at least one trip end in the road pricing zone). The attractions taken from destinations in the road pricing zone because of the destination shift elasticity e_d may then be redistributed to destinations outside the road pricing zone. A singly constrained entropy-maximising gravity model was used for this redistribution, see Taylor, Young and Bonsall (1996, pp.112-115)).

A value of travel time for peak period travel in Australian cities was chosen to be $12/h, in line with BTCE (1996)

Applications

Two applications of the stable of models have been made: Melbourne and Adelaide.

Melbourne

An initial application of the model was made to the Melbourne region as part of the 1997 urban air quality study conducted by the Australian Academy for Technological Sciences and Engineering (AATSE, 1997). In this study a road pricing zone was defined by a circular boundary drawn at a five km radius around the Melbourne CBD.

The base case for modelling was the user equilibrium solution corresponding to Wardrop's first principle (W-I). Model outputs from all other cases were compared to this. VHT, VKT and total car trips were least in the network-wide full marginal cost road pricing scenario. Marginal cost road pricing in the road pricing zone showed the second least number of car trips, VKT and VHT. In terms of air pollutant emissions generated by peak period road traffic, estimates were made for carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons (HC), oxides of nitrogen (NOX) and particulate lead (Pb), using the models described in Taylor (1996, 1998). Each road pricing scheme had different effects. Full marginal cost road pricing across the network had the largest impact on travel and emissions (VHT reduced by seven per cent, car trips by four per cent, and VKT by 3.5 per cent), whilst marginal cost road pricing and time-based road pricing in the CBD road pricing zone were the next most effective schemes. The levels of emissions of the pollutants largely followed the trends of the travel parameters, except perhaps for NOX. Decreases of between three per cent (for NOX) and six per cent (for HC) in overall emissions were estimated for the pollutant emissions in the marginal road pricing scenarios Differences of one to three per cent occurred for the other road pricing schemes – again the larger reductions were in HC emissions. The Melbourne results are described in more detail in AATSE (1997) and Taylor (1998).

Adelaide

The stable of network models has also been applied to the Adelaide metropolitan area This analysis considered peak period traffic flows and the air pollutant emissions effects in the network under a number of road pricing and travel demand management regimes:

- the *status quo* for 1991 (this being the time period which applied to the available travel demand data), using a user-optimum equilibrium assignment (W-I), a reasonable macro-level simulation of the existing travel pattern
- a system-wide assignment (W-II) in which the total vehicle-hours of travel (VHT) in the network are minimised (for the given travel demand task)
- full marginal cost road pricing in the entire metropolitan arterial road network
- the definition of a road pricing zone containing the Adelaide CBD. The road pricing zone was defined by a cordon line around the parkland belt surrounding the City of Adelaide local government area. A cordon charge of one dollar was then imposed on vehicles entering the road pricing zone in the morning peak
- imposition of a distance-based road pricing charge of $0.19 per kilometre on all vehicle journeys within the central Adelaide road pricing zone
- imposition of a time-base road pricing charge of $0.13 per minute of travel time on all vehicle journeys within the road pricing zone
- imposition of full marginal cost road pricing in the road pricing zone.

The Adelaide network analysed using the stable of models had 840 nodes, 2174 links (representing the main arterial road system) and 274 zones. The travel demand data was the 274 × 274 origin-destination matrix for car travel in the 1991 morning peak hour (Oxlad, 1997). Cheap and plentiful car parking in the Adelaide CBD minimises the effects of parking availability on car usage.

The model results are summarised in Figures 1-3. Figure 1 provides indications of the overall relative travel performance of the alternative road pricing regimes, using the initial user equilibrium flow distribution as a datum. Table 1 indicates the values plotted in Figure 1 and the summary statistics on which they are based. Table 2 provides the modelled values for the fuel and emissions performance of the user equilibrium assignment, whilst Table 3 indicates the relative fuel and emissions performance of the different road pricing regimes, as shown in Figures 2 and 3.

The three figures indicate the effects of network-wide marginal cost road pricing (MCRP) in reducing VHT, VKT, fuel and emissions, largely through a suppression of car travel (14 per cent less trips, 27 per cent less VHT, 15 per cent less VKT). MCRP restricted to the road pricing zone also shows reductions in travel, e.g. six per cent of car trips in the morning peak, 12 per cent less VHT and six per cent less VKT. Travel reductions from cordon pricing, distance-based pricing and time-based pricing yield modest decreases, of four per cent (time-based VHT) or less. Interesting the system-wide minimum VHT with fixed travel demand (W-II) reduces VHT by less than one per cent, compared to the user equilibrium solution (W-I).

Table 1: Summary travel statistics and relative performance (to user equilibrium solution) - metropolitan Adelaide network, 1991 am peak hour

	User equilibrium assignment (W-I)	Minimum VHT (W-II)	MCRP in full network	MCRP in RPZ	Cordon pricing for RPZ	Distance-based pricing in RPZ	Time-based pricing in RPZ
Trips	232 390	232 390	198 510	218 347	230 659	230 803	228 203
Total VHT	89 735.9	89 377.2	67 820.1	80 530.0	88 387.4	88 545.6	86 761.3
Total VKT	3 371 240	3 364 000	2 848 810	3 178 310	3 342 380	3 348 050	3 315 480
Relative values:							
Trips	1.000	1.000	0.854	0.940	0.993	0.993	0.982
Total VHT	1.000	0.995	0.724	0.875	0.981	0.984	0.959
Total VKT	1.000	0.997	0.844	0.938	0.991	0.992	0.982

MCRP = marginal cost road pricing *RPZ = road pricing zone*

Table 2: Network wide fuel and emissions rates for the user equilibrium assignment in the metropolitan Adelaide network, 1991 am peak hour

Unleaded petrol (L/100 vkt)	Leaded petrol (L/100 vkt)	CO2 (g/100 vkt)	CO (g/100 vkt)	HC (g/100 vkt)	NOX (g/100 vkt)
26.66	35.99	304.3	18.71	0.319	0.936

Table 3 Relative fuel and emissions performance in metropolitan Adelaide network, 1991 am peak hour (datum = user equilibrium assignment)

	User equilibrium assignment (W-I)	Minimum VHT (W-II)	MCRP in full network	MCRP in RPZ	Cordon pricing for RPZ	Distance-based pricing in RPZ	Time-based pricing in RPZ
Relative fuel and CO2 performance:							
Unleaded petrol	1.000	0.997	0.817	0.929	0.989	0.991	0.978
Leaded petrol	1.000	0.997	0.823	0.931	0.990	0.991	0.979
Carbon dioxide	1.000	0.997	0.820	0.930	0.990	0.991	0.979
Relative emissions performance:							
Carbon monoxide	1.000	0.998	0.833	0.937	0.991	0.992	0.981
Hydro-carbons	1.000	0.997	0.773	0.907	0.986	0.988	0.971
Nitrogen oxides	1.000	0.998	0.851	0.946	0.992	0.993	0.984

MCRP = marginal cost road pricing *RPZ = road pricing zone*

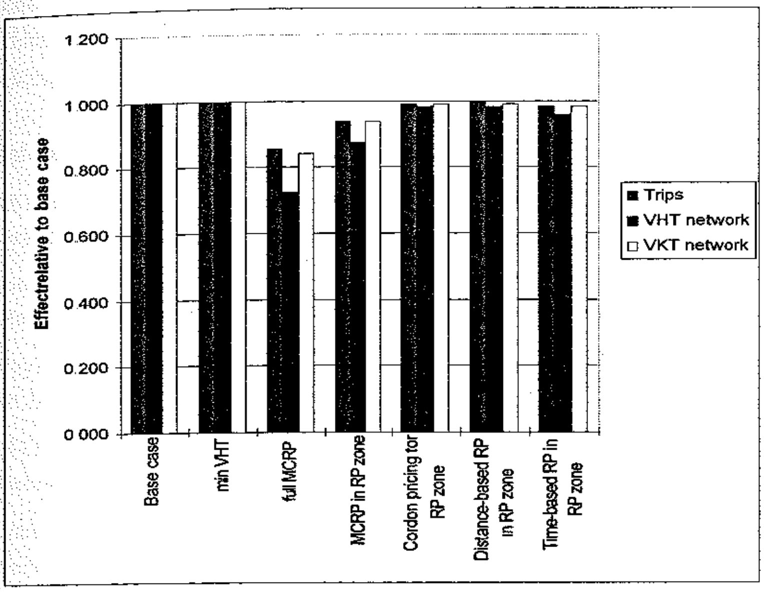

Figure 1: Summary travel statistics (1991 am peak trips, VHT and VKT) for the metropolitan Adelaide network, relative to the user equilibrium datum

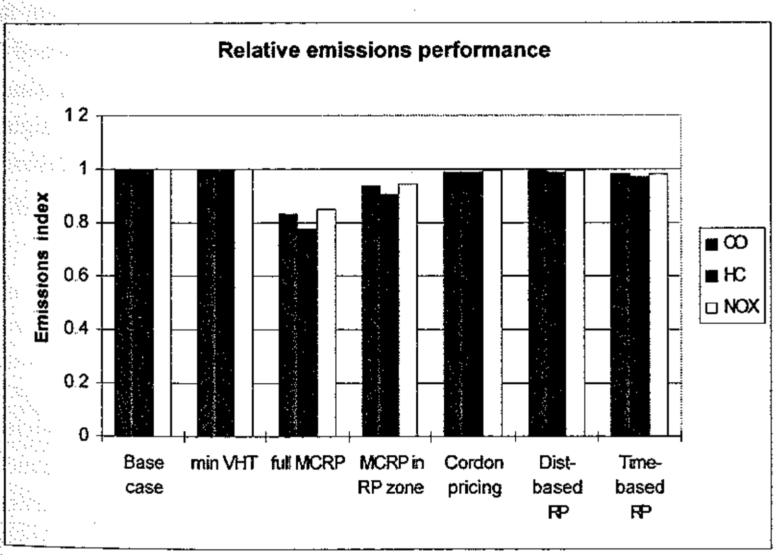

Figure 2: Summary emissions data (CO, HC and NOX) results for the metropolitan Adelaide network in the 1991 am peak

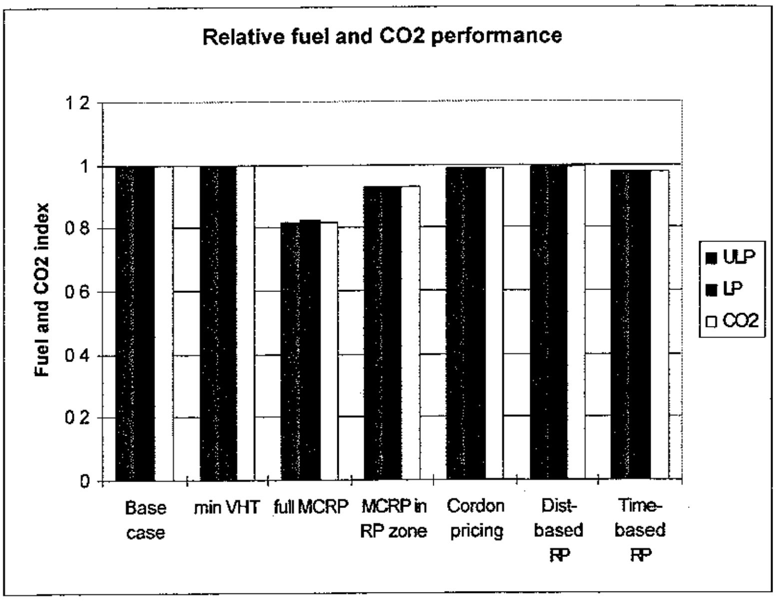

Figure 3: Summary fuel consumption and CO2 emissions results for the metropolitan Adelaide network in the 1991 am peak

As may be seen from Figures 2 and 3, full MCRP offers significant reductions in fuel consumption (about 18 per cent) and emissions (22 per cent for HC to 15 per cent for NOX). MCRP in the road pricing zone offers reductions of seven per cent in fuel and 5-10 per cent (NOX-HC) in emissions. The other road pricing regimes offer small percentage decreases (two per cent or less). For these regimes, selection of higher cordon, per km or per minute charges would be expected to lead to increased reductions. Ongoing research is looking at these charges, to find the values that would approximate the reductions indicated for MCRP in the road pricing zone.

Conclusions

This paper described the use of equilibrium assignment models for congested networks for testing the impacts of road pricing (and other travel demand management) policies, including modelling of emissions. Applications to two cities, Melbourne and Adelaide, were reported. Positive effects of road pricing under the options tested are indicated. Full marginal cost road pricing achieves the best model results in terms of car travel parameters and emissions. Time-based road pricing and distance based road pricing also produce positive results, though not quite to the same levels. Cordon pricing also has desired effects on emissions, although the single cordon price investigated in this study is not perhaps quite as efficient as the alternatives? Further work is required to test the effects of varying the cost parameters on the outcomes, although full marginal cost road pricing would be expected to achieve the greatest reductions in car travel and emissions.

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