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Environmental transport pricing based on air quality criteria

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Abstract

"Environmental transport pricing" may be a more politically acceptable than road pricing to achieve sustainable transport, where revenues can be earmarked to improve public transport, cycling and walking facilities. The maximum permissible amount of VKT in a defined study area is calculated so as not to exceed ambient air quality targets based on ambient carbon monoxide standards. A model (Optimum Road Pricing based on Environmental Capacity) is developed that extends the area-wide environmental capacity (AWEC) model with the inclusion of a travel demand model that is sensitive to road pricing. As meteorological conditions are dynamic, time-dependent charges are levied on motorists to reduce demand and achieve environmental targets. Five tolling schemes are modelled to determine optimum tolls: distance based; zone based; cordon based; distance-based marginal cost pricing (MCP), including the congestion cost (congestion time externalities); and distance-based environmental externality pricing.

A case study of model application is made of the transport network for the entral Area of Sydney using travel data for 1999. The result obtained for vehicle kilometres of travel (VKT) in the study area (base case) is then compared to the target VKT corresponding to the AWEC model. Meteorological conditions are incorporated in the AWEC model by the "ventilation rate" to reflect the mixing height of air and wind-speed. The optimum pricing level for each tolling scheme is selected accordingly to achieve the environmental standards. Optimum charges to the motorist (in 1999 prices) range from 8 to 20 cents/km, from 10 to 30 cents/per zone crossed, and from $1 to $3 per trip at the cordon.

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Introduction

For four decades, the possibility of implementing road-pricing schemes has been the centre of theoretical and political discussion. Despite real-world applications that have proven the technological feasibility of implementing complicated road-pricing schemes there remains strong political and community opposition to any imposition of additional tolls and taxes on motorists. A good example of this opposition is provided in the NSW Minister for Transport's response to the release of a three-year research study by the Warren Centre for Advanced Engineering, University of Sydney on "Sustainable Transport in Sustainable Cities" (*The Sydney Morning Herald*, 4 July, 2002). The political unpalatability of road pricing is well documented.

We argue that the concept should be re-packaged as environmental transport pricing that is based on a rationale that can garnish broader community support. The issue of metropolitan air quality is well documented and, in NSW for example, the Government's *Action for Air* has strong stakeholder commitment for implementation. Our approach to road pricing aims to determine how much to charge to ensure acceptable environmental quality whilst maintaining economical efficiency. The aim is to establish a credible, time-dependent, pricing regime whose rationale is transparent to a predominantly car-owning urban electorate. We note is passing of the desirability of integrated approaches to transport policy and the wisdom of allocating net revenues from our scheme to improving public transport, cycling and pedestrian facilities.

The approach integrates the concept of Area Wide Environmental Capacity (AWEC) of road traffic based on air quality criteria (Hidas, Shiran and Black, 1997) with road pricing as the specific travel demand management instrument to achieve an optimum traffic condition that fulfils both environmental and economical targets. Previous research has lead to the development of an AWEC model based on standards for carbon monoxide. This model is extended to the road-pricing problem by using the TransCAD platform on a test network for the Central Area of Sydney. The paper describes data sources, travel demand model structures, calibration parameters and the AWEC parameters for each grid cell of the study area. Finally, the main findings from the study are discussed along with directions for further research.

Area Wide Environmental Capacity (AWEC)

In the assessment of development applications and local environmental plans consultants sometimes provide calculations on whether the "environmental capacity" of an area would be exceeded on traffic grounds. The concept of the environmental capacity of a road link is well established in practice. Community surveys have established the importance of road traffic noise, pedestrian safety and vehicle emissions as the main criteria for an operational definition of environmental capacity. As airborne pollutants disperse over an area wider than the immediate road environment (Hidas, Shiran and Black 1997) have proposed the concept of Area Wide Environmental Capacity (AWEC), defined as the maximum permissible amount of VKT in a specified area that does not exceed ambient air quality standards (or future targets). The dependent variable in the model is the AWEC index – the ratio of forecast VKT by area divided by the permissible amount of VKT by area to meet ambient air quality standards under the specified meteorological conditions. The concept was illustrated using carbon monoxide standards as the limiting environmental factor, and an operational model was calibrated using traffic, transport and environmental data for the Sydney metropolitan region.

The measured concentrations of carbon monoxide at monitoring stations are a function of emission rates (from all sources) and local atmospheric and meteorological conditions. The dynamic complexity of nature has been incorporated into the AWEC model by using a composite explanatory variable called the ventilation rate - a function of the atmospheric mixing height and the wind speed, and abbreviated as VR – where the unit is the velocity of one cubic metre of air per second, m^2/s. Other statistically significant variables that explain carbon monoxide concentrations, in addition to road traffic (VKT by area) are road layouts, building orientation and land use parameters – such as the aspect ratio (AR) parameter, defined as the ratio of building height to the width of the adjacent street. The appropriate spatial units (km^2) for the analysis were found to be a function of AR, with the higher the AR the smaller the spatial unit for analysis.

Optimum Road Pricing Based on Environmental Capacity - ORPEC

The originality of the research reported in this paper is the integration of area-wide environmental capacity with road pricing schemes into one strategic planning model called OPREC - Optimum Road Pricing based on Environmental Capacity. The objective in the model is to set the road charges such that the vehicle kilometres travelled do not exceed the environmental capacity (based on carbon monoxide concentrations as a proxy for air quality) for a study area. As the environmental capacity varies with the meteorological conditions the argument is that charges rate should also vary by time of day. For a specific area (for example, a CBD) a range of environmental capacities in terms of VKT under various meteorological conditions (the ventilation rate) can be developed.

Applying a traditional 4-step travel demand model that is sensitive to price changes, unique road charges corresponding to each environmental capacity index can be formulated. This road charge ensures that vehicle kilometres travelled will be constrained to be less than the AWEC index of unity.

ORPEC Model Applied to Central Sydney

To demonstrate the application of ORPEC a case study to determine plausible environmental transport pricing for Central Sydney is undertaken. The study area covers about 14 square kilometres, including the Sydney CBD and part of North Sydney. A grid network of cells was overlayed on the study area, with each cell approximately 1 sq km in dimension. The vehicle kilometres travelled (VKT) as forecast by the travel demand model were aggregated for each cell of the grid. The analysis is confined to the morning peak hour in 1999. TransCAD is used as the analysis platform. TransCAD is a powerful and thorough geographic information system designed specifically for transport systems planning, management, and analysis. The GIS capability of TransCAD is used to aggregate the vehicle kilometre travelled within the defined spatial areas. The aggregated VKT is then compared with the AWEC parameter index derived from the AWEC model (Hidas, Shiran and Black, 1997) for each of these spatial areas.

Data

Input to the study is the NSW Department of Transport, Transport Data Centre Home Travel Surveys (HTS) for 1997-1999. Highway and public transport networks were obtained from NSW Roads and Traffic Authority and from the Transport Data Centre. The highway networks were provided in emme/2 format and were then imported into TransCAD. Morning peak-hour trip tables were extracted from household travel survey data and then aggregated into three trip purposes (home based work – HBW; home based non-work – HBNW; and non-home based NHB). Modes of travel were also aggregated into three major groups: public transport – PT; car - C; and other - O, where the first two groups include all motorised trips.

Mode choice

Only the impact of pricing on mode and route choice of travellers was considered. (Other impacts may include: change in the choice of time-of-day for travel; change in destination; and the decision not to travel – but these are ignored in our analysis because of limitations of available data.) Using both highway and public transport network skims, an incremental binary logit mode choice model was then calibrated for each trip purpose - HBW, HBNW and NHB. The utility function for the car modes for three trip purposes contains explanatory variables for the value of time by car for each trip purpose (in $/minute); the amount of toll payed (in $); the average cost of parking in the city centre; the distance travelled by a car (in kilometres); and the vehicle operating cost (in $/km). The utility functions by trip purpose for public transport contain the following variables: public transport system wait time in minutes; travel time to access the public transport system in minutes; and time spent in-vehicle travelling by public transport.

Route choice

For route choice analysis a multi-class stochastic user equilibrium assignment procedure of TransCAD was used with three user classes (trip purposes) and corresponding values of time.

Value of time

A key parameter in this analysis of appropriate prices to charge motorists is the value of time. There are two aspects to this: the behavioural value and the economic (resource) value of time. The behavioural value is used in the mode choice and route choice process. The economic value is used in developing the congestion-related marginal social cost charges. The behavioural values of time have been extracted from recent studies in New Zealand and their comparison with latest available data for Sydney. The economic value of time has been extracted from economic analysis manual with adjustments to exclude commercial and heavy vehicles from the reported value (Roads and Traffic Authority of New South Wales, 1999, Appendix B, pp. B1-B5). The values of time used in this study are all in 1999 prices:

> Behavioural Value of Time: HBW $10.08 per veh-hour; HBNW $13.86 per veh-hour; NHB $15.96 per veh-hour.
>
> Economic Value of Time: $10.75 per veh-hour.

AWEC parameters and ventilation rates

The AWEC parameters for different ventilation rates used for the analysis were developed after reviewing and adjusting the values reported by Hidas, Shiran and Black (1997). Table 1 below shows the adopted values for this study.

Table 1 AWEC for Sydney CBD and Ventilation Rates

VR- m^2/s	AWEC- VKT/hr- km^2
0-300	15,000
300-850	20,000
850	30,000

Modelling Base Case VKT/AWEC

The application of the AWEC model and the travel demand model allowed an estimate to be made for the base case (1999) network of the VKT in each cell of the study area and the environmental capacity based on carbon monoxide criterion (expressed in VKT per cell) for three different meteorological conditions. The purpose of this exercise is to explore those parts of the study area where traffic exceeds the calculated environmental capacity, and where pricing schemes are justified.

In the base case scenario total vehicle kilometre travelled within the target area for the morning peak hour in 1999 is about 259,000. Aggregating the VKT travelled within each cell shows that CBD, North Sydney north and North Sydney west have the highest VKT. The VKT at cell level exceeds AWEC for most of the cells in the lower ventilation rate scenario (VR above 850 m^2/s). For the medium ventilation rate scenario SYD-S, CBD, CBD-N, N-SYD-W and N-SYD-N exceed the AWEC. In the highest ventilation rate scenario (VR from 0 to 300 m^2/s) only the CBD has a VKT greater than the AWEC criterion. Based on these preliminary appraisals, three cells were selected for further assessment of pricing schemes: N.Syd, CBD and CBD-N.

Environmental Transport Pricing (Road Pricing) Scenarios

A two digit coding protocol is used for identifying each road-pricing scheme, “MN”. Where “M” indicates the road pricing structure and “N” defines the basis for calculation of optimum pricing. Three road pricing structures were identified

- Scheme A: Distance Based;
- Scheme B: Zone Based;
- Scheme C: Cordon Based.

There are three scenarios for the optimum toll under each toll structure. Scenario 1 is based on AWEC, scenario 2 is based on charging only the externality cost of air pollution, and scenario 3 is based on charging the marginal social cost of travel, including congestion and the environment.

In the distance-based pricing scenario charges are calculated and applied to each link inside the road-pricing area. In the cordon scenario charges are applied to vehicles when crossing the cordon on the boundaries of the pricing area. In the zone-based pricing scenario charges are applied when vehicles cross the boundaries of each zone. The optimum toll determined under distance-based schemes for marginal pricing scenarios (Scenarios A2 and A3 in Table 2), is considered as the first practical best solution for marginal cost pricing. The optimum charges for scenarios 2 and 3, under Schemes B and C, are those charges that would result in the closest transport system status to A2 and A3, respectively. Table 2 shows the scenarios assessed.

Table 2 Road-Pricing Schemes for Analysis and Assessment

Item	Scheme Type	Basis for calculation of road charges	Scheme code
1	Distance based	AWEC	A1
2	Distance based	Environmental Externality MC*	A2
3	Distance based	Congestion externality MC	A3
4	Zone based	AWEC	B1
5	Zone based	Environmental Externality MC	B2
6	Zone based	Congestion externality MC	B3
7	Cordon based	AWEC	C1
8	Cordon based	Environmental Externality MC	C2
9	Cordon based	Congestion externality MC	C3

* Marginal Cost

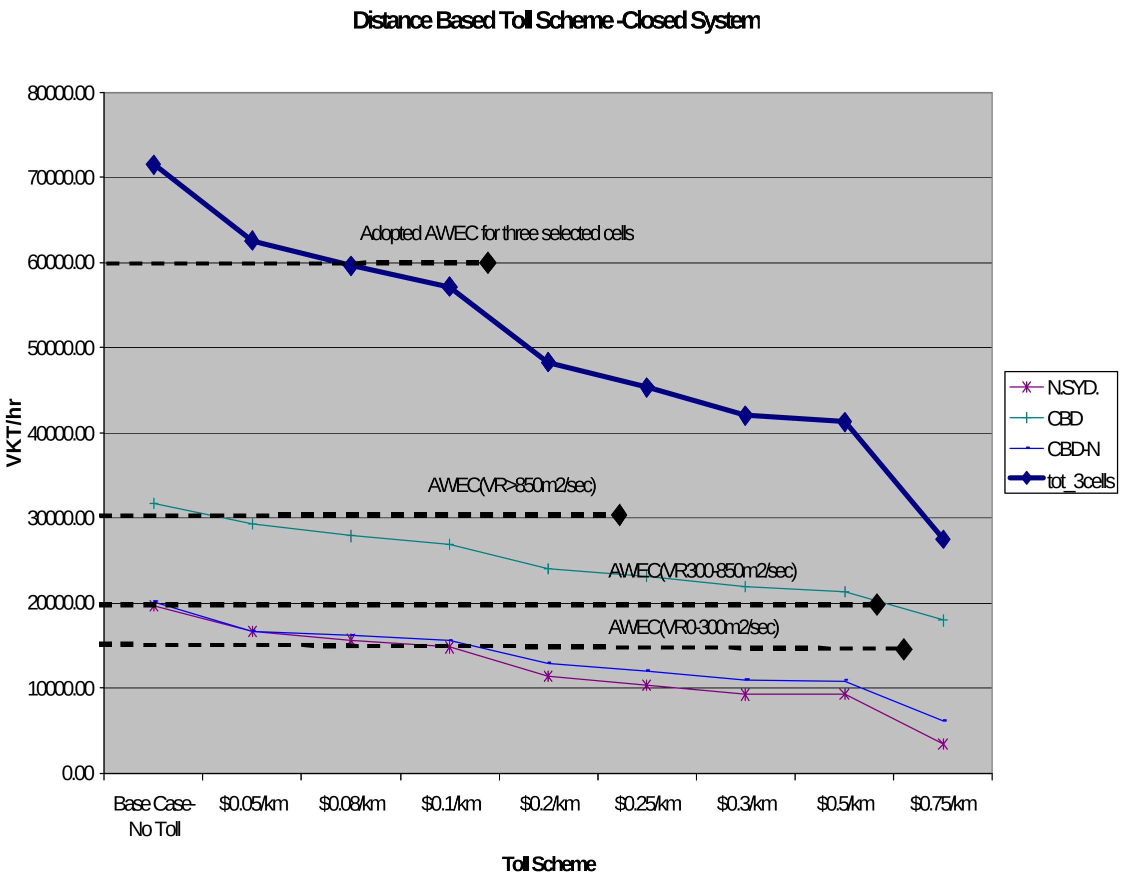
After running the model, and aggregating the travelled vehicle kilometre for a range of pricing levels, demand curves are developed that show the change in VKT for selected cells (or combination of cells) against the change in pricing level. For each meteorological scenario, the optimum price for each scheme is then determined as the charge that meets the AWEC target.

Results

Distance-based road pricing

Distance-based road pricing is a scheme where the amount each vehicle is charged is calculated based on the distance the vehicle has travelled, applying a fixed charge rate per kilometre. The curve showing the relationship between VKT and the charge rates were estimated to give the optimum prices that result in a lower VKT than the AWEC for selected cells or a combination of cells. Figure 1 shows the vehicle kilometres travelled within selected cells under each toll scheme. The figure includes graphs for three grid cells and a graph for the total of the three.

Figure 1 VKT by Range of Charge Rates for Distance-Based Pricing



As shown in the figure, in the base case scenario (no toll scheme), the total VKT for each of the three cells and their combination exceeds the AWEC for the lowest ventilation rate scenario. Under the lower ventilation rate the AWEC for each grid cell is equal to 15,000 vehicle kilometres travelled per hour, and for the three-cell combination the AWEC is 45,000. For each of the three ventilation scenarios, two optimum prices are identified: the first value would result in lower vehicle kilometres of travel than AWEC for each individual cell; the second optimum price is based on the lower VKT for the combination of the three cells. Under the first scenario, the optimum price would be 75 cents per kilometre and for the second scenario (three cell total VKT lower than the adopted AWEC for the total of three cells), the optimum price would be 25 cents per kilometre.

For the medium ventilation rate, the adopted AWEC for each individual cell is 20,000 vehicle kilometres travelled per hour. AWEC for the combination of three cells would be 60, 000 vehicle kilometre per hour. The optimum prices are 55 cents per kilometre and 8 cents per kilometre, respectively. The significant difference between the three cells combination and the individual cell optimum price is because the total vehicle kilometres of travel for the CBD cell is significantly higher than the other two cells in the base case scenario. Under the base case scenario the vehicle kilometre for the CBD cell is more than 31,000 vehicle kilometres of travel compared to 20,000 for the other two cells. This may justify a different pricing scheme, or even a change in highway network operations (direction of flows) to spread the traffic to other cells.

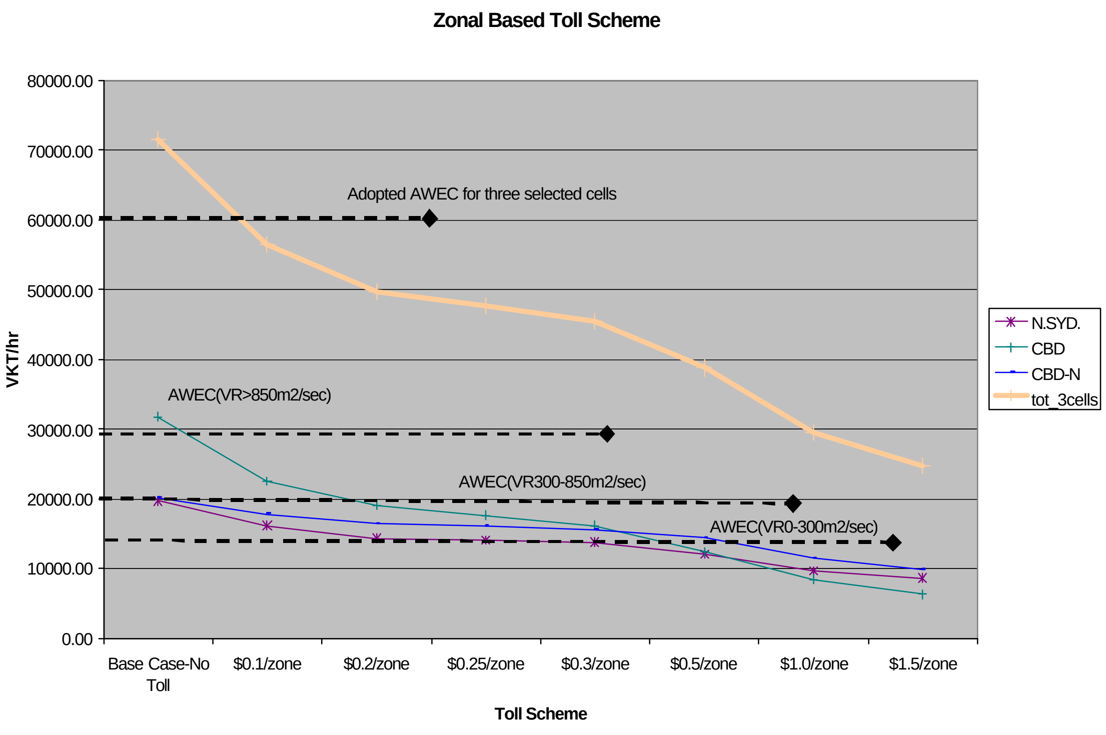
For the higher ventilation scenario, only the CBD has higher vehicle kilometres of travel than the adopted AWEC criterion. The total vehicle kilometres of travel for the three selected cells are lower than the adopted AWEC criterion. This means no charge would be required under this meteorological condition. If the objective were to keep the vehicle kilometres of travel lower than the AWEC target for each individual cell then the optimum charge would be 5 cents per kilometre.

Zone-based road pricing

Zone-based road pricing is a pricing regime in which the project area is divided in to a set of sub zones. Vehicles are charged each time they enter (or depart) a zone. It is similar to cordon-based pricing with multiple cordons in place. The study area of central Sydney has been divided to 6 pricing zones. The model was run for a series of charge rates for crossing each zone. The curves showing the relationship between VKT and charge rates were estimated. The optimum charge rates for entering/leaving zones that would result in a lower VKT than the AWEC target are derived from the model for selected cell, or a combination of cells. Additional model runs were undertaken. Figure 2 shows the VKT within selected cells under each toll scheme. The figure includes graphs for three grid cells and a graph for the total of the three. For each of three ventilation scenarios, two sets of optimum pricing are identified. The first value would result in lower vehicle kilometres of travel than the AWEC criterion for each individual cell. The second optimum price is based on lower VKT for the combination of three cells. Under the first scenario, the optimum pricing would be 75 cents per zone boundary crossing, whereas for the second scenario the optimum pricing would be 30 cents per zone.

For the medium ventilation rate, the optimum price for individual cell and three cells combination are 20 cents per zone and 8 cents per zone, respectively. For the higher ventilation scenario, only the CBD has higher vehicle kilometres of travel than the adopted AWEC criterion. The total vehicle kilometres of travel for the three selected cells are lower than the adopted AWEC. This means no charge would be required under this meteorological condition. If the objective were to keep the vehicle kilometres of travel lower than AWEC for each individual cell the optimum charge would be 5 cents per zone crossing.

Figure 2 VKT by Range of Charge Rates for Zone-Based Pricing



Cordon-based road pricing

Figure 3 shows the vehicle kilometres of travel within selected cells under each toll scheme. The figure includes graphs for three grid cells and a graph for the total of the three. Under the first scenario, the optimum price would be $5 for crossing the cordon line whereas for the second scenario (three cell total VKT lower than the adopted AWEC for the total area), the optimum charge would be $3.

For the medium ventilation rate, the optimum charges are $1.5 and $0.8 corresponding to the individual cell and the three cells combined, respectively.

The marginal cost pricing schemes are simulated in the model on a distance-based pricing basis. This is because the marginal costs in the literature are reported based on vehicle kilometres travelled. If vehicles are charged exactly for the cost they impose to society, the charging system is called the first-best solution. However, if the system is not capable of charging the full charge, and the scheme is based on cordon line pricing or zone pricing, then the second best solution is selected which results in the closest VKT to the first best solution. The results of these schemes are then compared to the ORPEC results.

Two major elements of the social costs of travelling vehicles are congestion (delay) cost and environmental damage. The marginal externality cost of congestion is calculated by applying an economic value of time of $10.75 per hour to each vehicle. The marginal congestion time has been calculated based on calculating the derivative of the volume delay function (BPR formula) and multiplying it by the number of vehicles travelling along the link. This is equivalent to the additional travel time each vehicle imposes on other travellers. This additional social delay is then multiplied by the economic value of time as mentioned above. An average estimate of environmental external costs of transport in Australia adopted by Bray and Tisato (1998) is shown in the Table 3.

Table 3 Environmental External Costs in 1996 Prices (Source: by Tisato and Bray, 1998)

External Cost Item	Cost - cents per vehicle-km
Noise	0.3
Global warming	2.0
Local air pollution	2.0
Water pollution	0.3
Environmental costs - Total	4.6

Some of the environmental cost items such as global warming and water pollution have less local impacts and are usually independent of the time and location of the emission. To show the difference, the charge rates have been varied from 2 cents per km to 5 cents. Figure 4 shows the results of the analyses for the congestion plus environmental social cost pricing. This will also cover the difference between 1996 and 1999 prices. As shown in the graph, with 5 cents per vehicle kilometre as the environmental social cost and full congestion social cost the vehicle kilometres of travel would be higher than the AWEC criterion for the three-cell combination - both for the medium and low ventilation rate scenarios. It should be noted that the external cost of global warming and water pollution, have a global and regional impact rather than a local one. They are independent of time of day, and can be addressed by imposing a fuel tax or other forms of charges (Sterner 1998, pp.150-151).

Figure 4 VKT by Range of Charge Rates for Distance-Based Marginal Social Cost Pricing (Including Congestion Costs)

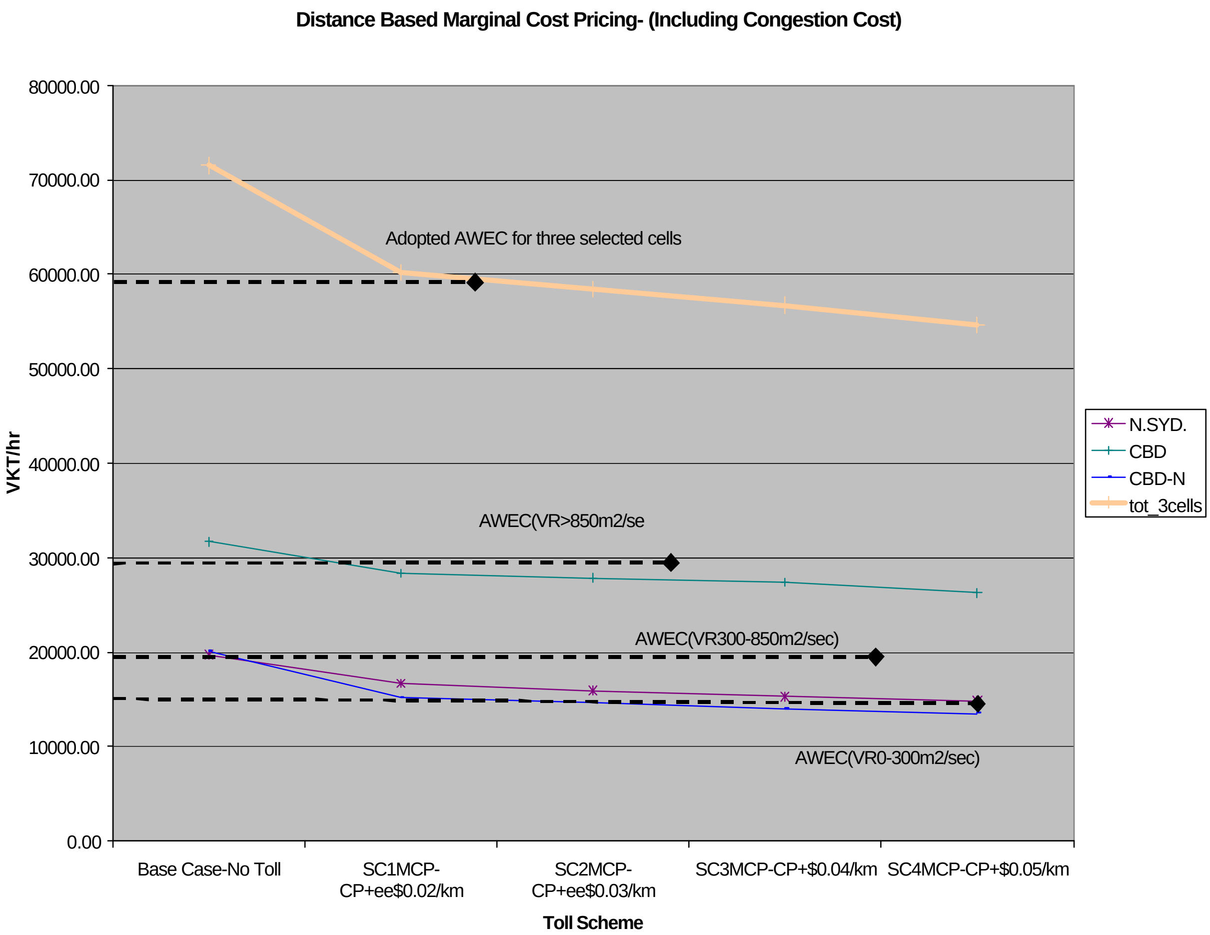
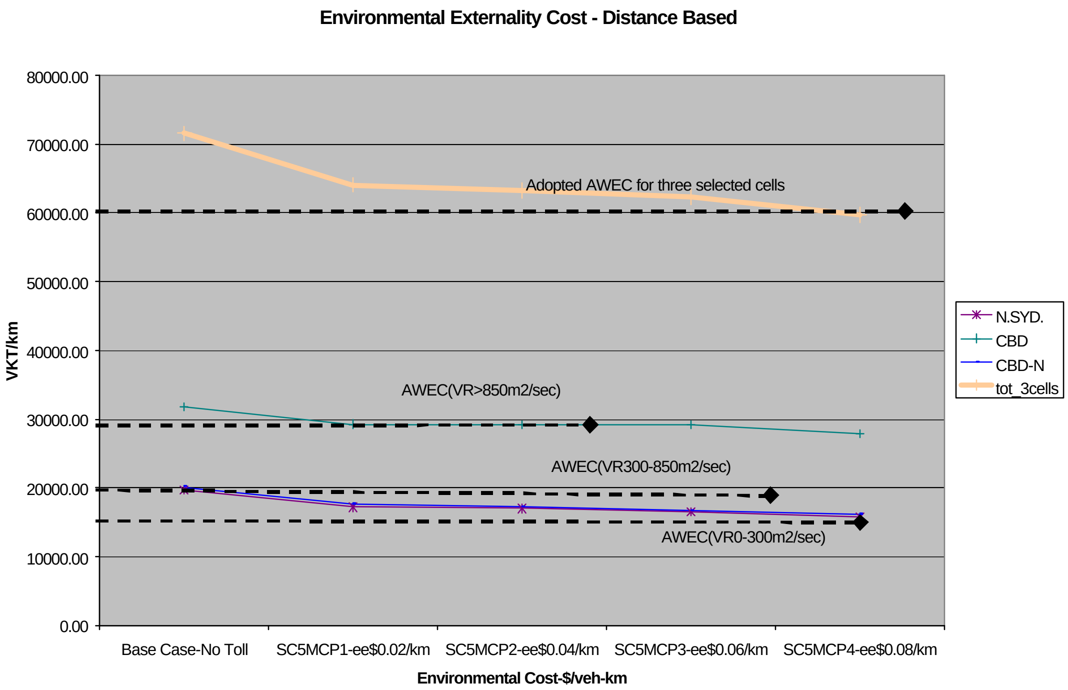


Figure 5 shows the result of analysis for the selected area and the combination of selected cells. In this scheme only the environmental externality cost of traffic is considered in calculating the charges. The range of charges varies from 2 to 8 cents per vehicle kilometre (sixty percent higher than the average estimates by Tisato and Bray shown in Table 3- including the global warming and water pollution costs). As the graph in Figure 5 shows that even with the 60 percent higher charge attached to the environmental externalities none of the cells meet the AWEC under the low ventilation ratescenario. For the medium ventilation ratethe vehicle kilometres of travel in the three cells are still higher than the AWEC criterion.

Figure 5 VKT by Range of Charge Rates for Distance-Based Marginal Social Cost (Environmental Externality Costs Only)



Results and Discussion

From the analyses presented above, a number of observations can be made about the different pricing schemes examined and the optimum level of environmental transport prices.

(a) Marginal environmental cost pricing (based on data in Table 3) does not assure target air quality standards being met; AWEC-based pricing (target oriented) is the most rational way to achieve ambient air quality standards.

(b) Optimum environmental charges vary by meteorological conditions (ventilation rates, as defined in the AWEC theory), and variable pricing regime, for which the enabling technology is available, is required with three qualitative meteorological conditions appearing to be a practical compromise on this highly dynamic and time dependent phenomenon.

(c) Under favourable conditions of atmospheric dispersal (VR 450 m^2/s) there will be days that no environmental charge is required (VR450 m^2/s). However, on those days the charge should only reflect the congestion marginal costs to assure economic efficiency.

(d) Distance-based pricing has the largest impact on the level of VKT for grid cells.

(e) Cordon-based pricing has the highest impact on mode shift, but the maximum VKT at the cell level does not drop by the same amount as for distance-based pricing. The location of the cordon is the determining factor.

(f) In the full marginal social cost pricing scenario, the charges have been calculated and applied at the link level. They can be considered as the first-best solution. The equivalent distance-based, zone-based and cordon-based best charges are summarised in Table 4.

Table 4 Second-Best Solution for Sydney CBD with Marginal Congestion and Environmental Pricing

Scheme	Distance-based equivalent	Zone-based equivalent	Cordon-based equivalent
Congestion and Environmental social cost	15 cents/veh-km	15 cents/zone crossing	$1.1/ cordon crossing

Finally, we suggest that the best way to determine optimum toll values is the maximum of the charge based on AWEC and marginal social cost (congestion i) pricing. Table 5 shows the proposed charge rates for any distance-based, zone-based or cordon-based scheme, as a function of varying meteorological conditions. When the ventilation rate of VR 450 m^2/s, and where the AWEC is higher than the actual base case for 1999, the charge rates are determined in Table 5 based on the second-best solution to marginal cost pricing, as described above.

Table 5 Proposed Road Pricing Charges for Sydney- Maximum of AWEC-Based and Marginal Cost Pricing

Pricing Scheme		Optimum toll value		
		AWEC - Ventilation Rate 0-300	AWEC - Ventilation Rate 300-450	AWEC - Ventilation Rate 450
Environmental capacity based pricing	Distance Based	20 c/km (80c)*	15* c/km (60c)	15* c/km
	Zone Based	30 c/zone (50c)	15*c/zone (20c)	15* c/zone
	Cordon Based	$3 ($5)	$–1.1* ($1.75)	$1.1*

Two charges are shown, X (Y): X is the optimum toll based on AWEC for the selected individual cells and Y in parentheses is the combination of the three grid cells chosen from the study area
*Charges will be based on marginal social cost rather than AWEC

Conclusions

The ORPEC (Optimum Road Pricing based on Environmental Capacity) model integrates the well-established concept of Area Wide Environmental Capacity (AWEC) of road traffic based on air quality criteria (carbon monoxide standards) with a traditional four-step travel demand model that includes road pricing to achieve an optimum traffic condition in a study area. that the aim is to fulfil both environmental and economical targets. The application of the model using the TransCAD platform on a test network for the Central Area of Sydney has been outlined along with data sources, travel demand model structures, calibration parameters and the AWEC parameters for each grid cell of the study area. The base case is morning peak-hour traffic in the study area in 1999.

The base case (1999) peak hour traffic simulation for the study area indicates a total vehicle kilometres of travel (VKT) of about 259 000. Depending on meteorological conditions, different charges to motorists are set so as to dampen private vehicle demand (VKT) to a level that will ensure ambient air quality standards (for carbon monoxide) are met. Three road-pricing structures are examined: distance based; zone based; and cordon based. The results of the analysis are presented graphically showing the optimum toll charged, the representative meteorological conditions, the AWEC index, and the estimated reduction in VKT in the study area to achieve the air quality target. Different pricing schemes reduce VKT in the study are to from 70 to 82 per cent of the base case traffic.

The model has been applied to examine different pricing schemes and toll charges for three representative meteorological conditions. The optimum toll to achieve traffic levels (as measured by VKT) that meet the air quality standard (for carbon monoxide) is estimated. We conclude that the best way to determine these optimum toll values is the maximum of the charge based on AWEC and on marginal social cost (congestion included) pricing – the latter when meteorological conditions are highly favourable for dispersion, and where there would be no need to reduce the base case traffic (VKT) on air quality grounds alone. Representative charges to the motorist (in 1999 prices) range from 15 to 20 cents/km, from 15 to 30 cents/per zone crossed, and from $1.1 to $3 at the cordon – with the location of the latter an important determinant on the toll charged (Table 5). Further research is required into AWEC models with different emission characteristics followed by an application of the kind described here to test optimum environmental transport prices.

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