COST EXTERNALITIES AND ROAD PRICING EVALUATION: EXPERIMENTAL FINDINGS FROM NETWORK ANALYSIS

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Abstract
The analysis of cost externalities in the evaluation of road pricing schemes based upon a network analysis in Christchurch (New Zealand) is presented. Results indicate that current practices do not suit the special characteristics of road pricing analysis and evaluation. Road charging may create negative benefits for society and its main purpose (increasing transportation efficiency) may not reached as well.

1. Introduction

The prospects of implementing road pricing schemes in urban areas have attracted a great deal of attention in recent years. Reports of the Singapore and London experiences have encouraged many transportation planning agencies to examine the prospects of road pricing implementation (Transport for London, 2003). Based on the results of these experiences, it has been argued that road pricing constitutes a planning instrument, which can be used to reach transportation planning objectives, because it directly affects road user behaviour. On the other hand, concerns have been expressed about the long-tem impacts and reliability of road pricing project evaluations.

In the scientific literature, recent road pricing modelling efforts can be classified as theoretical or practical studies. On the theoretical side, studies such as Yan and Lam (1996), Yang and Huang (1998), de Palma *et al* (2005), Yperman *et al* (2005), Meng *et al* (2005) and Zhang and Levinson (2005) have concentrated in analysing marginal cost charging either for first best road pricing (general network) or second and third best charging schemes (bridges, tunnels, motorways, etc) considering hypothetical road networks. On the other hand, various practical pricing case studies such as Gupta *et al* (2005), May and Milne (2005), Sapirova (2005) and Sumalee *et al* (2005) has mostly contemplated valuation and assessment of travel time, travel cost and travel distance benefits associated with charging schemes by applying a large variety of optimisation techniques (e.g.: genetic algorithms, game theory, etc).

Although there are several practical motivations and considerable scientific progress has been achieved, the implications of cost externalities associated with travel demand behavior modelling have still to be examined in details. Current project evaluation practices estimate the benefits mainly from the minimization or the reduction of the network-wide travel time, which is obtained through the estimation of traffic flows on the network (Meyer and Miller, 1994). For the evaluation of road pricing schemes, it is assumed that the road network can be controlled in order to reach the best use of the road capacity, through charging the marginal cost in order to minimise the road system travel time (cost). However, it is essential to verify whether economic efficiency is reached through the minimization of the system travel time. This specifically implies that the traffic assignment modelling and forecasting results have to be examined for the special case of road pricing schemes. It is also important to expand the

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analysis to incorporate the social impacts generated by road pricing schemes. The consideration of external costs that are not currently part of the analysis may affect the results of the evaluation of road pricing schemes.

This paper presents the analysis of cost externalities in the evaluation of road pricing schemes based upon network analysis. After this brief introduction, we examine the state-of-the art network modelling concepts in order to assess the impact of cost externalities in road pricing evaluation. An application of these modelling concepts to a case study in Christchurch, is described. Conclusions are summarized in the final section.

2. Modelling cost externalities impacts in road pricing evaluation

This section presents the main modelling definitions, assumptions and procedures as well as the formulation of cost functions to analyse the impacts of cost externalities in the evaluation of road pricing.

2.1. Modelling definitions

To conduct the modelling of network users' behaviour under road charging conditions, two distinct principles are enunciated:

- All users make their route choices in order to minimise their perceived travel time (cost) up to a point of equilibrium at which the travel time (cost) on all used routes is less than or equal to that on the unused routes (i.e. Wardrop's first principle), which can be expressed mathematically as an optimization problem as:

$$T^e = \sum_{a \in L} \int_0^{f_a} c_a(f_a)dx \qquad (1)$$

subject to

$$\sum_{a \in L} h_r = d_{pq}, \quad p \in P; q \in Q \qquad (1a)$$

$$f_a = \sum_{pq} \sum_{r \in R_{pq}} h_r \delta_r^a, \qquad a \in A \qquad (1b)$$

Where

$T^e =$	total network cost at the point of equilibrium e;
$h_{pqr} =$	traffic flow from origin p to destination q on the route r;
$c_a(f_a) =$	travel cost on the link a for a flow f_a
$d_{pq} =$	demand for trips from origin p to destination q;
$\delta_{pqr}^a =$	1 (if the link a is on the route r from p to q) or 0 (otherwise);
L=	set of links in the network;
P=	set of origin nodes;
Q=	set of destination nodes; and
A=	set of links as part of route;

- With control of the road network, the best use of road capacity is reached through charging the marginal cost in order to minimise the system total cost (i.e. Wardrop's second principle). This can be expressed mathematically as:

$$T^o = \sum_{a \in L} \int_0^{f_a} c_a^m(f_a)dx \qquad (2)$$

Subject to conditions expressed in equations 1a and 1b, where:

$T^O =$ Total network cost at the point of system equilibrium *O*;

$c_a^{\,m}\left(f_a\right) =$ marginal travel cost on the link *a* for a flow f_a;

On one hand, Equation 1 expresses the current practice adopted in project evaluation, which considers the minimization of travel costs to estimate benefits. On the other hand, Equation 2 supports Bell and Iida's (1997) observation that road pricing is the mechanism for applying marginal charges that are the difference between marginal and average costs. Furthermore, the economic theory suggests that the most efficient allocation of resources results when travellers pay the marginal cost inclusive of the externalities.

2.2. Modelling assumptions

The main assumption adopted here is that users can be charged in terms of their direct usage of the road network and/or in terms of indirect costs such as noise, air pollution and accidents. This assumption is ambitious in nature and maybe unrealistic to a certain degree, because its implementation would be almost impossible using the technology and knowledge currently available. Nevertheless, it relates to reality to the extent that direct and indirect impacts occur every time a road user makes a trip, but they are not actually accountable for the impacts of their actions.

2.3. Modelling procedure

This comprises four steps. Firstly, relevant data about both supply and demand are prepared for analysis. For simplicity the demand (i.e. origin-destination or OD flows) is assumed to be fixed within the study network. On the supply side, physical network characteristics, such as free flow speeds and link capacities, have to be defined *a priori.*

The second step involves the selection of the appropriate cost functions and assignment methods, in order to establish the interaction between supply and demand. Two descriptive types of cost functions are employed: perceived cost and social cost. In transportation practice and research, perceived cost is often represented by travel time only, due to its simplicity and major contribution to the total perceived cost. The Bureau of Public Roads (BPR) travel time function is the best known and mostly commonly applied in transportation studies (Thomas, 1991). On the other hand, social cost consists of three aspects: efficiency, energy and environment effects. In the social cost function, total travel time represents the economic efficiency of transportation system and total fuel consumption represents energy sustainability, while accidents, pollution and noise costs take account of environmental sustainability.

Among assignment methods, user equilibrium (UE) assignment with the classic BPR cost function is initially used to estimate the unregulated traffic pattern. Then road pricing is assumed to be implemented throughout the network by charging users the marginal cost, which Bell and Iida (1997) defined as the user optimum (UO), because the minimum travel cost (time) is achieved from the users' point of view. From the public perspective, the social optimum (SO) is estimated by minimising the total social cost. The social equilibrium (SE) assignment approach (where users are assumed to minimise the perceived social costs of their own travel) is used merely for comparison purposes.

In the fourth step, the assignment types are established on the basis of the combinations of cost functions and traffic assignment methods, as shown in Table 1. It can be seen from the last column of Table 1 that all the assignments are conducted using the UE approach, since it has been mathematically proven that the system optimum assignment can be identified through user equilibrium assignment with marginal costs (Newell, 1980; Mao, 2004). For example, the SO assignment involves the optimal allocation of traffic based on the social cost, and can be accomplished by the UE assignment method with marginal social costs. Based on the UO traffic assignment, the implementation of a road pricing scheme is simulated. For all assignment types (UE, UO, SO and SE), the total travel time value and social cost are calculated and compared. The total travel time values indicate whether the road pricing is efficient in monetary terms, while the social cost is used to examine whether it creates benefits to the society. This will also be used to verify the impact of the cost externalities in the assessment of road pricing schemes.

Table 1 – Assignment definitions

Assignment type	**Description**	**Accomplished by UE with**
UE	minimising users' perceived costs (time)	perceived costs
UO	minimising total user travel cost (time)	marginal costs
SE	minimising users' social costs	social costs
SO	minimising total social cost	marginal social costs

2.4. Formulation of cost functions

User costs differ from the user perceived costs, which are often represented by time cost functions or generalised cost function. Instead the economic values of time and fuel consumption can be calculated dynamically according to average travel speeds on individual links.

The list of external costs, however, is almost endless. For instance there are twelve components in environmental assessment recommended by HMSO (1993) in the UK, namely air quality, cultural heritage, disruption due to construction, ecology and nature conservation, landscape effects, vehicle travellers, water quality and drainage, geology and soils, and policy and plans. Since it is impossible to consider them all, some major components should be taken into account, which are costs of accidents; road construction, maintenance and services; and environmental externalities such as air pollution and noise (Small, 1992).

Taking into consideration Transfund NZ's Project Evaluation Manual (PEM) (Transfund 2002), the following sub-sections describe the cost functions for user's perceived cost, social cost and marginal costs.

2.4.1. Perceived cost

The classic BPR cost function is shown in Equation 1, where the free flow time is t_0, and the link flow is f and the link capacity is C. The parameters α and β are estimated to fit the relationship to the observed traffic flow characteristics in the absence of road pricing.

$$t = t_0 \cdot \left(1 + \alpha \cdot \left(\frac{f}{C}\right)^{\beta}\right) \tag{3}$$

2.4.2. Social cost

Social cost (*SC*) is the summation of the travel time cost (*TTC*), operating cost (*OC*), accident cost (*AC*), air pollution cost (*APC*) and noise cost (*NC*) in monetary terms (NZ$), as represented in Equation 4.

$$SC = TTC + OC + AC + APC + NC \tag{4}$$

The travel time cost is defined by Transfund (2002) as the base value of travel time in un-congested conditions ($16.27/vehicle/hour) plus the additional value of travel time due to congestion ($3.95/vehicle/hour). Therefore, after applying these two values to Equation 3, the travel time cost of a vehicle on a link is

$$TTC = \frac{t_0}{60}\left(16.27 + 3.95\alpha\left(\frac{f}{C}\right)^{\beta}\right) \tag{5}$$

As for the vehicle operating cost on a link, Transfund's Manual (2002) recommends the application of Equation 6.

$$OC = \begin{Bmatrix} 12.672 + 18.854[\ln(v)] - 8.7295[\ln(v)]^2 + 1.0424[\ln(v)]^3 + \\ \exp(-12.2911 + 26.6027[vc] - 13.0656[vc]^2) \end{Bmatrix} / 100L \tag{6}$$

where

L	link length (km);
v	travel speed (km/hour) on a link; and
vc	minimum value in the range $\left[1.0; \frac{f}{C}\right]$.

For the third component (accident cost), the average cost for vehicles travelling on a link is estimated using the following equation.

$$AC = 0.03 \cdot f^{0.08} \cdot L \tag{7}$$

The air pollution cost is the most imprecise one among the social costs, with Transfund (2002) suggesting that a light vehicle travelling at 40 km/hour has an air pollution cost of 1 cent per km. It is not unreasonable to assume the average speed is 40 km/hour in the peak hour given that traffic in the network is slightly congested. Hence, the air pollution cost of a vehicle on a link is calculated as follows.

$$APC = 0.01 \cdot \ell \tag{8}$$

where ℓ is the length of the link.

As for the last component of social cost, the average noise cost per vehicle per hour on a link is calculated as shown in Equation 9, assuming that the ambient noise level is 55 dB network-wide (HMSO 1975) and the monetary value for a link is determined according to Transfund (2002).

$$NC = 0.0217\left(10\log_{10} Q_T + 33\log_{10}\left(v + 400 + \frac{500}{v}\right) - 98.7\right)NH / f \tag{9}$$

where

NH is the number of households along the link; and

Q_T is the daily traffic volume (AADT, vehicles per 18 hours a day).

2.4.3. Marginal costs

On the basis of Equation 3, the marginal cost is as follows.

$$t = t_0 \left(1 + \alpha(\beta + 1) \left(\frac{f}{C} \right)^{\beta} \right) \quad (10)$$

The marginal social cost can be derived from the social cost and the derivation is not presented here due to the limited space (see Mao, 2004 for details).

3. Case study

This section describes the application of the concepts presented in section 2 to conduct network analysis experiments that aim to assess the impact of cost externalities in the evaluation of a road pricing scheme in Christchurch, New Zealand.

The following sub-sections describe the study area, the database, modelling results and analysis.

3.1 Description of the study area and the database

The study area comprises the Greater Christchurch Metropolitan area, which gathers an approximately 350 thousand inhabitants of 130,500 households with approximately 200,000 cars. The area is covered by an extensive network, which includes main arterial roads such as the Main North Road, Main South Road, Riccarton Road, Blenheim Road, Colombo Street, QE II Drive, Southern Motorway and Northern Motorway. Figure 1 shows the study area and its main urban elements.

Previous planning and modelling activities (e.g. Christchurch Transportation Study - CTS) have divided the study area into 559 zones, including 10 external zones, and reserving 81 zones for the future usage. Figures 2 and 3 show, respectively, the zones and the network used in this study. The network data was obtained from the Traffic Model (1996) developed jointly by the Christchurch City Council, Environment Canterbury and Transit New Zealand. and consists of basically residential zones. The road network database (road lengths, capacity, travel time, etc) was obtained from the Christchurch City Council and was geo-referenced in a Geographical Information System (GIS) according to the New Zealand Map Grid.

This study considered an Origin-Destination matrix comprising 471 traffic zones, representing a total demand of 88115 trips in the morning peak (8-9 AM).

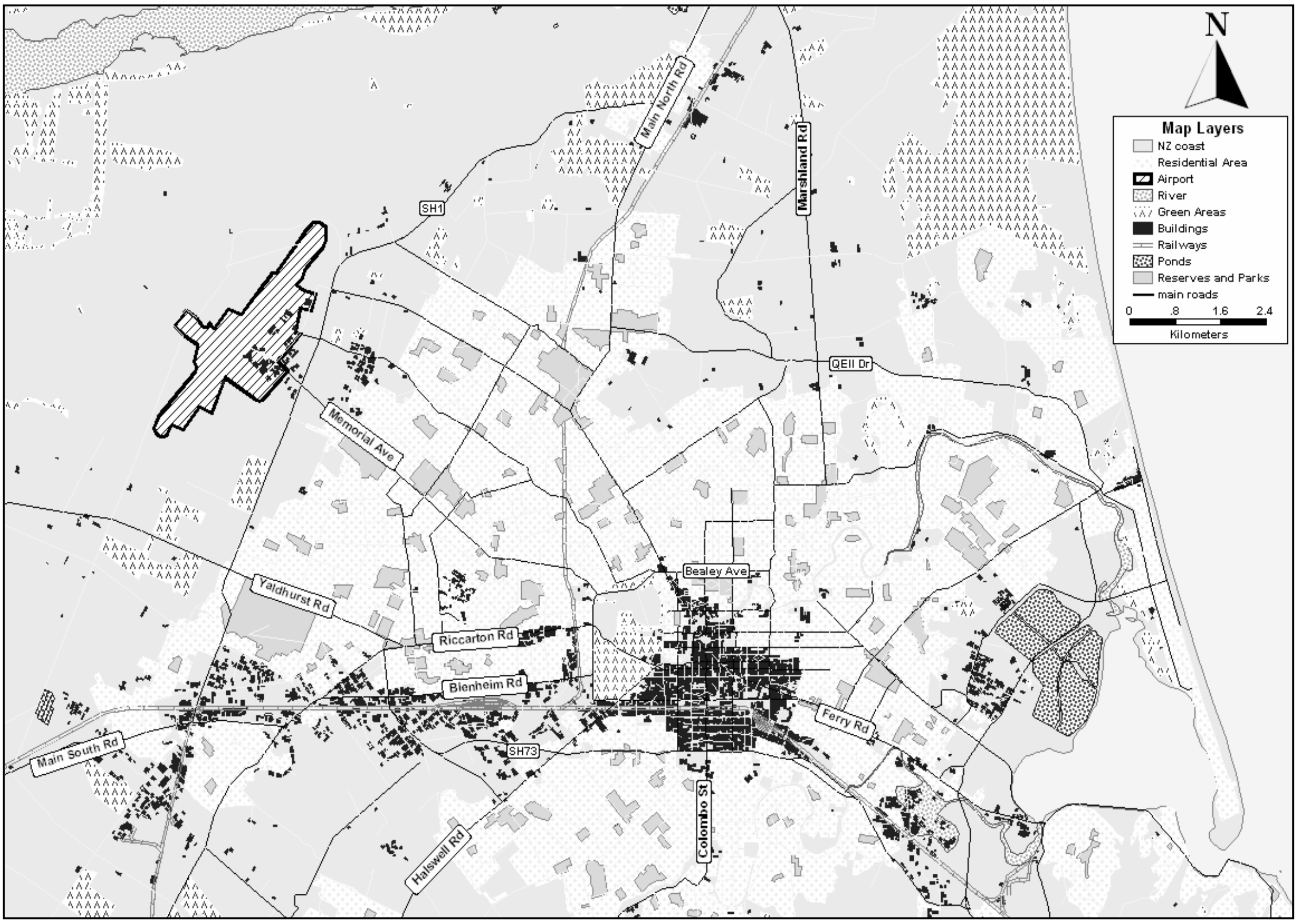


Figure 1 – Main elements of the study area

Figure 2 – Traffic zones

Figure 3 – Road Network

3.2. Modelling results

The cost functions (Equations 4-10) were implemented in a Transportation Planning package (TransCAD) in order to conduct the four assignments (UE, UO, SE and SO) as defined in Table 1.

Initially, the UE assignment with the BPR cost function (Equation 3) was used to reproduce the current traffic flow pattern. After 8 iterations considering a convergence rate of 0.01, constants α and β in the BPR function were calibrated (Equation 11). For a relative gap of 0.01, equilibrium was reached for an observed Root Mean Square Error (RMSE, defined in equation 12) of 34.16 trips with maximum flow change of 349.82 trips. The total number of vehicle*hours was 776845.51 and the total number of vehicle*Km was 649366.224. The assigned volume/capacity (VOC) ratios are shown in Figure 4.

$$t = t_0\left(1 + 0.38\left(\frac{f}{C}\right)^{3.7}\right) \qquad (11)$$

The four assignments (UE, UO, SE and SO) were carried out for the current network configuration, and the total travel times, travel time costs and social costs are listed in Table 2 and graphically represented in Figure 5.

$$RMSE = \frac{\sqrt{\sum \left(f - f^{e}\right)^{2}}}{n} \qquad (12)$$

where

f^e estimated traffic flow; and

n number of links with observed traffic flow f;

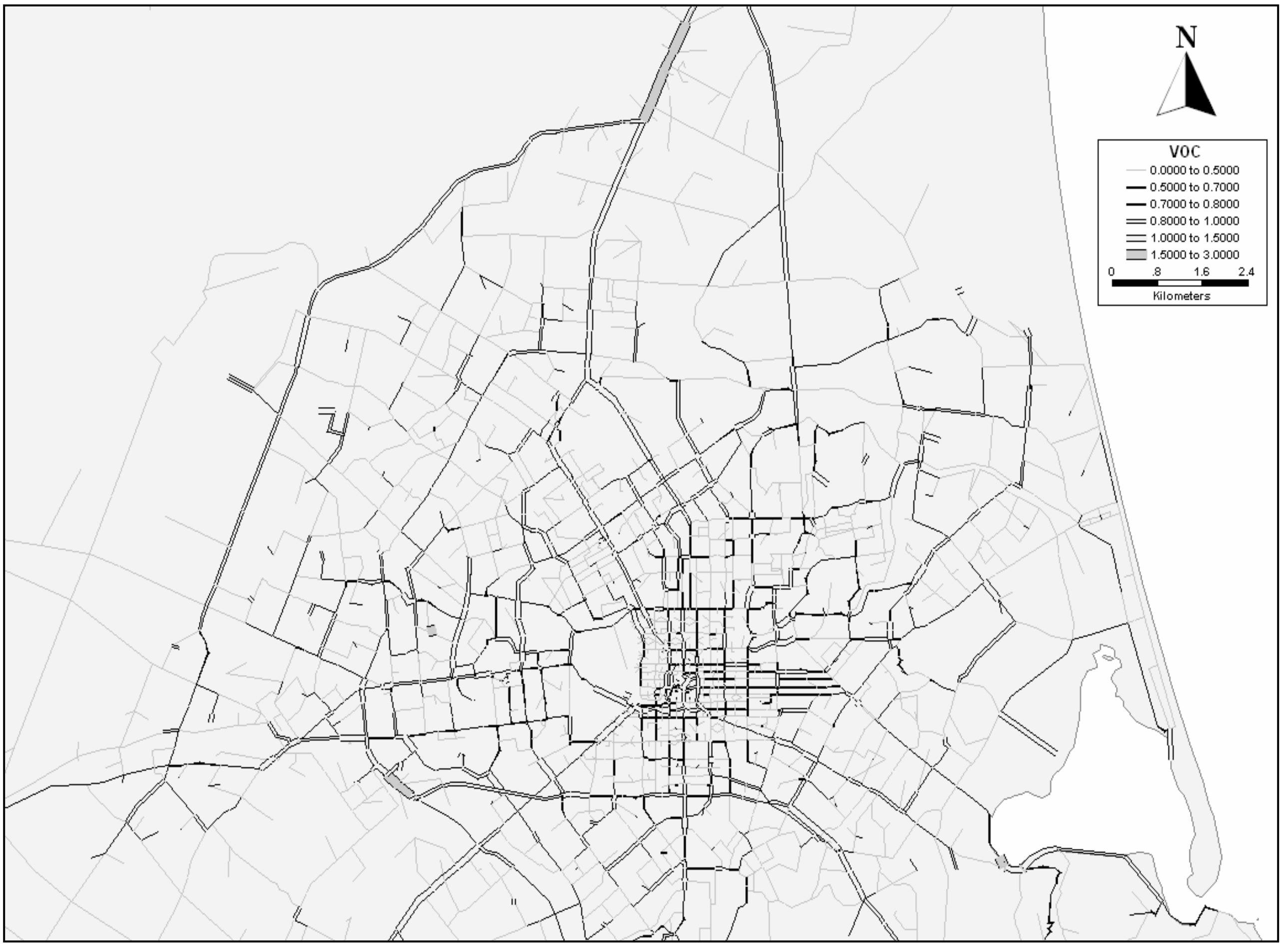
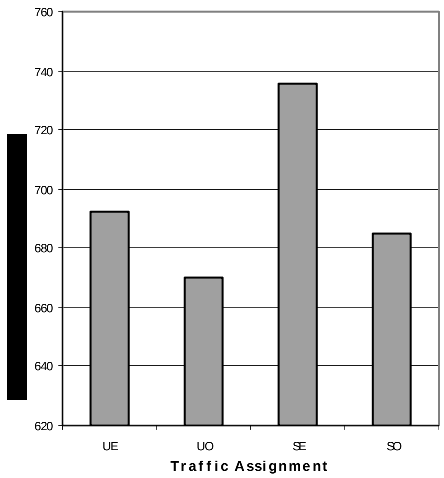


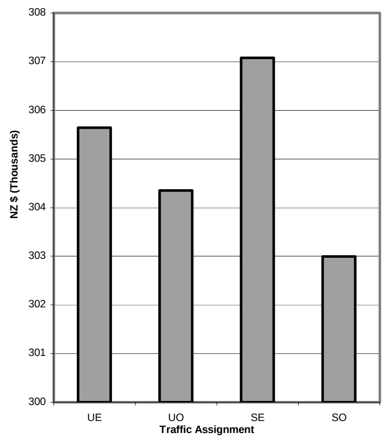
Figure 4 – Reproduced VOC

Table 2 – The results of the four assignments

	Assignment			
	UE	UO	SE	SO
Total travel time (veh-min) *(% increase from UE)*	692,113 *(NA)*	669,982 *(-3.2)*	735,366 *(6.2)*	684,850 *(-1.0)*
Total Social Cost (NZ$) *(% increase from UE)*	305,646 *(NA)*	304,351 *(-0.4)*	307,080 *(0.5)*	302,994 *(-0.9)*



(a)



(b)

Figure 5 – Traffic Assignment results: (a) Network Travel Time; (b) Network Social Cost

It can be seen that system-wide road pricing (UO) results in the minimum total travel time (692,113 vehicles-minutes). Its benefit results from the travel time saving of 22,131veh-min when compared with the assumed current travel pattern (UE). The SE assignment gives the largest travel time (approximately 6.2% more than the UE result), which is mostly due to the incorporation of external factors (accident, noise and pollution) into the cost functions The SO assignment does decrease the total travel time but not as much as for the UO assignment.

As for the total social cost, the SO assignment provides the lowest social cost for the system (NZ$302,994). The highest value occurs for the SE assignment, which is approximately 0.5% more than the UE results. Also interesting to note the composition of the social costs; this is approximately the same proportion of costs for all four types of assignments (travel time cost=56%; vehicle operational cost=31%; accidents costs=9%; air pollution costs=2%; noise costs=2%)

3.3. Analysis of the results

The results described in section 3.2 indicate that there is a clear relationship between network performance measures (total travel time cost and total social cost) and the four types of traffic assignment (UE, UO, SE and SO) reflecting different road pricing schemes. For each network performance measure, the results are different for each traffic assignment (UE, UO, SO and SE). For instance, the network performance results considering travel time show that the performance will be best with the introduction of a road pricing scheme (UO assignment). Furthermore, using the total social cost as the performance measure leads to the conclusion that a road pricing scheme (UO), which excludes social costs, would not be the best possible policy available

Consequently, it appears that totally different decisions will be reached depending on which traffic assignment and performance measures are employed. This is particularly interesting, because the outcomes present a great deal of contradiction among themselves. Current practices of evaluation, which convert travel time costs after traffic assignment, may lead to a decision that at the same time disregard the economic feasibility and the social impacts. As shown in Figure 6, the contradiction between the selection of the total travel time and total social costs is obvious, because if one takes the total travel time axis as the reference for comparison, the User Optimum (UO) is clearly the best option. However, if the total social cost axis is taken, then UO is actually far from the best option (SO). In contrast, the Social Optimum (SO) minimizes the adverse impacts, because it simultaneously optimizes the traffic pattern while accounting for the external costs. On the other hand, the Social Equilibrium (SE) option is extremely inefficient, because it allows road users to make their route choice decisions.

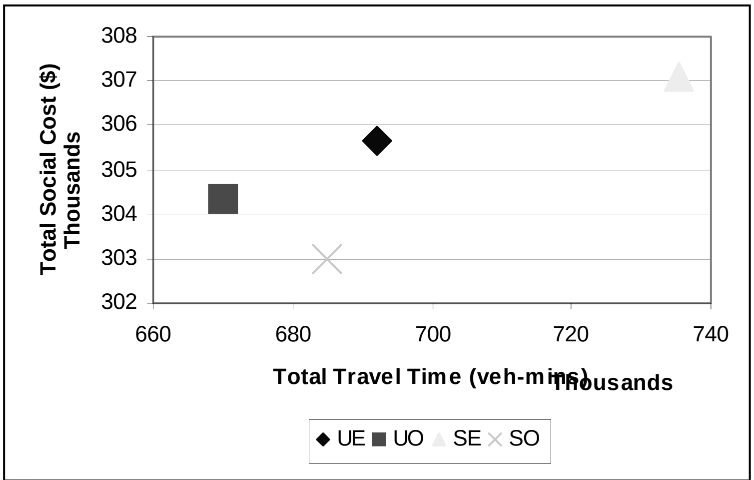


Figure 6 – Traffic Assignment results: Network Travel Time *versus* Network Social Cost

4. Conclusions

This paper attempts to contribute to the scientific and technical discussion regarding the analysis and evaluation of road pricing schemes. Among the many issues related to the implementation of road pricing schemes that have been discussed, the analysis and evaluation has a critical role in measuring, quantifying and comparing the benefits, costs and impacts that may be created from the implementation of road pricing. In this paper, we discussed the reliability of current practices for road pricing analysis evaluation, based on a method that provides a comparative analysis of the benefits and costs associated with interventional and non-interventional policies, as well as the incorporation of broad social impacts.

It was found that the application of current practices does not suit the special characteristics of road pricing analysis and evaluation. Current practices concentrate on the minimization of travel time, which is contradictory to the nature of road pricing schemes, which are heavily based on charging users the marginal travel costs.

The main consequence of this assessment of current practices is that technical decisions may be made based on erroneous grounds. In the case study, the road pricing benefits claimed by efficiently allocating the resources (road capacity) are partially predicted and some effects are not included. It was found that the implementation of road pricing minimising total travel time (UO) may make society worse off by imposing a greater total social cost than the non-interventional traffic (UE). This means that a form of road charging which excludes social costs may create negative social benefits for society.

There is a dilemma in that these assignments (the UE, UO and SO assignments) have their own advantages and disadvantages. The UE has near-optimal social cost and largest total travel time. The UO has minimum total travel time but a high level of social cost, whilst the SO minimises the social cost and causes more total travel time than the UO. Nevertheless, the SO is based on the monetary evaluation of all major costs and if this evaluation is sound, it delivers the best answer to maximising economic benefits and minimising the adverse impacts of transportation. The SO calls for social road pricing minimising the total social cost, rather than road pricing to minimise the travel time.

As for future studies, efforts should be made to allow for elastic demand. If the cost of travel is to be increased, the aim would not be to simply change the distribution of traffic on a network, but to reduce the amount of travel.

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