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ANALYSIS AND EVALUATION OF ROAD PRICING BENEFITS AND COSTS

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RESUMO
Apresenta-se o estudo dos benefícios e custos de projetos de pedágio urbano (*road pricing*). Propõe-se um método para estimar os benefícios e custos de iniciativas de pedágio urbano, buscando examinar os impactos econômicos e sociais gerados em decorrência desse tipo de intervenção. Esse método incorpora a combinação de diversos tipos de funções de custo e métodos de alocação de viagens, que possibilitam analisar comparativamente os benefícios e os custos obtidos para os usuários e o sistema de transporte. O método é aplicado a um estudo de caso em Christchurch, Nova Zelândia e os resultados mostram que as práticas atuais de implementação do pedágio urbano, baseadas na minimização do tempo de viagem, podem gerar um sistema de transporte mais ineficiente do que aquele sem qualquer intervenção. Observa-se também que a otimização social permite a minimização dos custos sociais e consequentemente cria mais benefícios para sociedade como um todo.

ABSTRACT
A study of the benefits and costs of road pricing projects is presented. A method for estimating the benefits and costs of road pricing initiatives to examine the economic and social impacts created from this type of intervention is introduced. This method incorporates the combination of several types of cost functions and traffic assignment methods, to allow the comparative analysis of the benefits and costs created for users and the transportation system. The method is applied in a case study in Christchurch, New Zealand, and the results show that current road pricing practices, based on travel time minimization, may create a transportation system which is more inefficient than not intervening. It is also observed that social optimization allows the minimization of social costs and consequently it creates more benefits for society as a whole.

1. INTRODUCTION

There has been a great deal of discussion about the prospects of implementing road pricing schemes in urban areas. These schemes include measures such as parking fees, taxes and road charges, which involve road users paying to use certain sections of roads or cordoned areas (Small and Ibannez, 1998). 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 theory and practice, there are several motivations for applying road pricing. According to Bell and Iida (1997), road pricing is the mechanism to apply 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. Nagurney (2000) pointed out that although Pigou raised road pricing as a concept as early as 1920, it has been used principally to address congestion problems. Indeed, current road pricing policy for congestion relief is notably concerned about travel time both in cost functions and project evaluations (Stenman and Sterner, 1998). More recently, utilising road pricing has been investigated as a policy instrument for reducingof the adverse impacts on the environment, including air pollution, accidents and noise (Button and Verhoef, 1998). This trend is driven by a rapid increase in the awareness of the environmental effects of transport and the advent of Intelligent Transportation Systems (ITS) (Stenman and Sterner, 1998).

Nevertheless, given the pervasive impacts of any long-term transportation policy and massive implementation costs of road pricing, its claimed benefits and adverse impacts have to be carefully investigated. Current practices of project evaluation 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). It is assumed that all travellers 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). 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. This is reached through charging the marginal cost in order to minimise the road system travel time (cost), in accordane with Wardrop's second principle (Ortuzar and Willumsen, 1995).

Despite the wide acceptance of these state-of-art practices and methods for the analysis and evaluation of transportation projects, there are some concerns regarding their use to assess road pricing schemes. Firstly, 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. Secondly, it is also important to expand the scope of the 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 a study of the benefits and costs of road pricing projects. A method for estimating the benefits and costs of road pricing initiatives is used to examine the economic and social impacts created by this type of intervention. The method is applied in Christchurch (New Zealand) to assess the practical consequences in a case study situation.

This paper is divided into four sections. After this introduction, the second section presents a description of the method for the analysis of road pricing benefits and costs. The third section describes the application of the method to the case study in Christchurch (New Zealand). Finally, the fourth section summarizes the findings of the research and makes some recommendations for further studies.

2. METHOD FOR THE ANALYSIS OF ROAD PRICING BENEFITS AND COSTS

In order to examine the benefits and costs of road pricing schemes, the method incorporates a combination of several types of cost functions and traffic assignment methods, to allow a comparative analysis of the benefits and costs created for users and the transportation system.

The method comprises five 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 accident, 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 created 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.

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

The fifth step involves the computation of the traffic assignments as defined in Table 1. 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.

3. CASE STUDY

The method described in the previous section was applied to a case study as follows.

3.1 Description of the study area and the database

The study area (Figure 1) is located to the northwest of the Central Business District (CBD) of Christchurch (New Zealand) and consists of basically residential zones. To the northwest of the study area, the International Airport is connected to the city by Memorial Avenue and Fendalton Road. To the south of the study area there is an industrial area, bounded by a railway corridor to the south of Blenheim Road. The western suburbs are connected to the CBD via the Memorial/Fendalton, Riccarton/Yaldhurst and Blenheim Road corridors. The major north-south movements are carried by the Greers/Waimairi/Peer/Curletts Road corridor.

The road network database,(road lengths, capacity, travel time, etc) was obtained from the Christchurch City Council and was geo-referenced in TransCAD according to the New Zealand Map Grid.

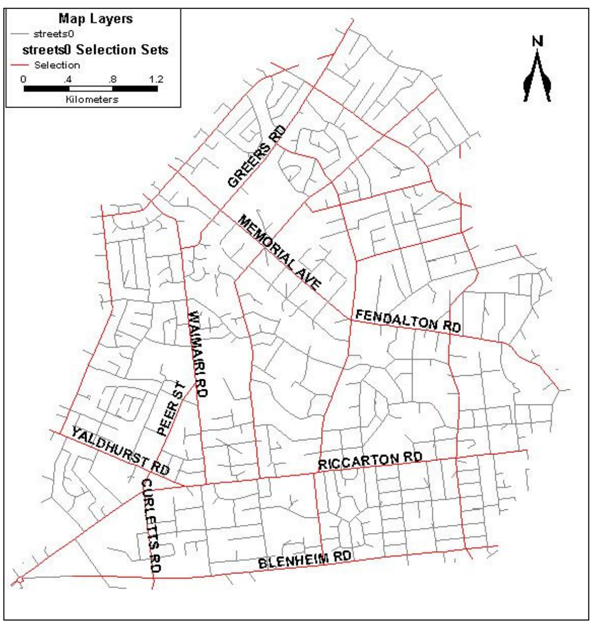


Figure 1 – Road network of the study area

The traffic flows for the morning peak (8.00 am to 9.00 am) was assigned to the network, which comprised 131 zones (including 94 internal zones). The O/D flows between zones were assumed to be fixed for simplicity of analysis and ease of comparison.

3.2 Cost functions

As noted above, travellers generally perceive their journey time as the travel cost, with the social cost consisting user and external costs. This paper attempts to include major components of the social cost (the travel time, vehicle operating, accident, air pollution and noise costs). All monetary evaluation was based on Transfund NZ's Project Evaluation Manual (PEM) (Transfund 2002), and was assumed that all the vehicles within the network are passenger cars. In the following sub-sections the cost functions are described.

3.2.1 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 represent the situation of unregulated traffic.

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

3.2.2 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 2.

$$SC = TTC + OC + AC + APC + NC \tag{2}$$

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 1, the travel time cost of a vehicle on a link is

$$TTC = \frac{t_0}{60}\left(16.27 + 3.95\alpha\left(\frac{f}{C}\right)^{\beta}\right) \tag{3}$$

As for the vehicle operating cost on a link, Transfund's Manual (2002) recommends the application of Equation 4.

$$OC = \begin{cases} 12.672 + 18.854[\ln(v)] - 8.7295[\ln(v)]^2 + 1.0424[\ln(v)]^3 + \\ \exp\left(-12.2911 + 26.6027[vc] - 13.0656[vc]^2\right) \end{cases} /100L \tag{4}$$

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.

$$AC = 0.03 \cdot f^{0.08} \cdot L \tag{5}$$

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

(7)

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.

$$APC = 0.01 \cdot L$$

As the last component of social cost, the average noise cost per vehicle per hour on a link is calculated as shown in the Equation 8, 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).

$$NC = 0.0217\left(10\log_{10} Q_T + 33\log_{10}\left(v + 400 + \frac{500}{v}\right) - 98.7\right)NH / f \tag{8}$$

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).

3.2.3 Marginal costs
On the basis of Equation 1, the marginal cost is as follows.

$$t = t_0\left(1 + \alpha(\beta + 1)\left(\frac{f}{C}\right)^{\beta}\right) \tag{9}$$

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).

3.3 Traffic assignments
The above cost functions were implemented in TransCAD in order to conduct the four assignments (UE, UO, SE and SO). In the next sub-sections, the results for each of these assignments are presented.

3.3.1 UE - reproduction of the current traffic
The UE assignment with the BPR cost function (Equation 1) was used to reproduce the current traffic flow pattern. Constants α and β in the BPR function were calibrated and are shown in Equation 10.The assigned volume/capacity (VOC) ratios are shown in Figure 2.

$$t = t_0\left(1 + 0.36\left(\frac{f}{C}\right)^{4}\right) \tag{10}$$

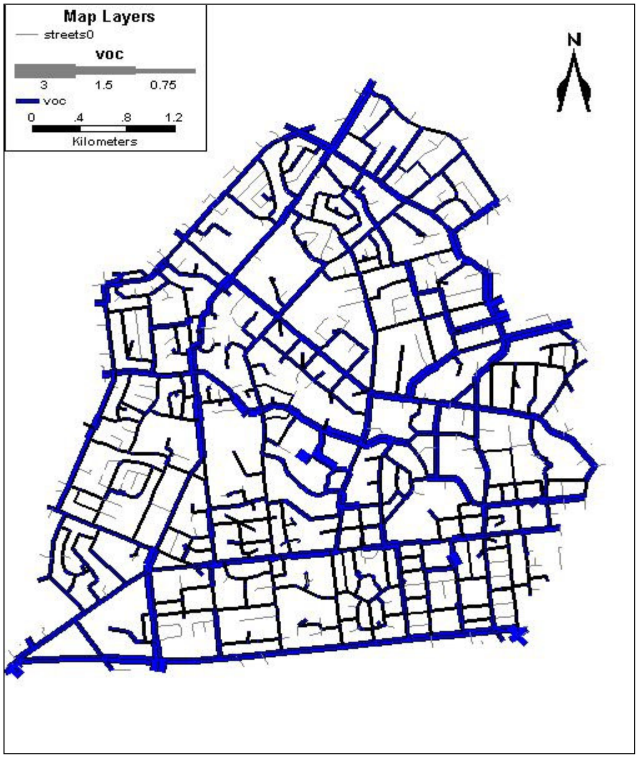


Figure 2 – Reproduced VOC

3.3.2 Results of the assignments

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 3.

It can be seen that system-wide road pricing (UO) results in the minimum total travel time (57435 vehicles-minutes). Its benefit results from the travel time saving of 2,836 veh-min when compared with the current travel pattern (UE). The SE assignment gives the largest travel time (approximately 11% more than the UO 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 no much as for the UE assignment.

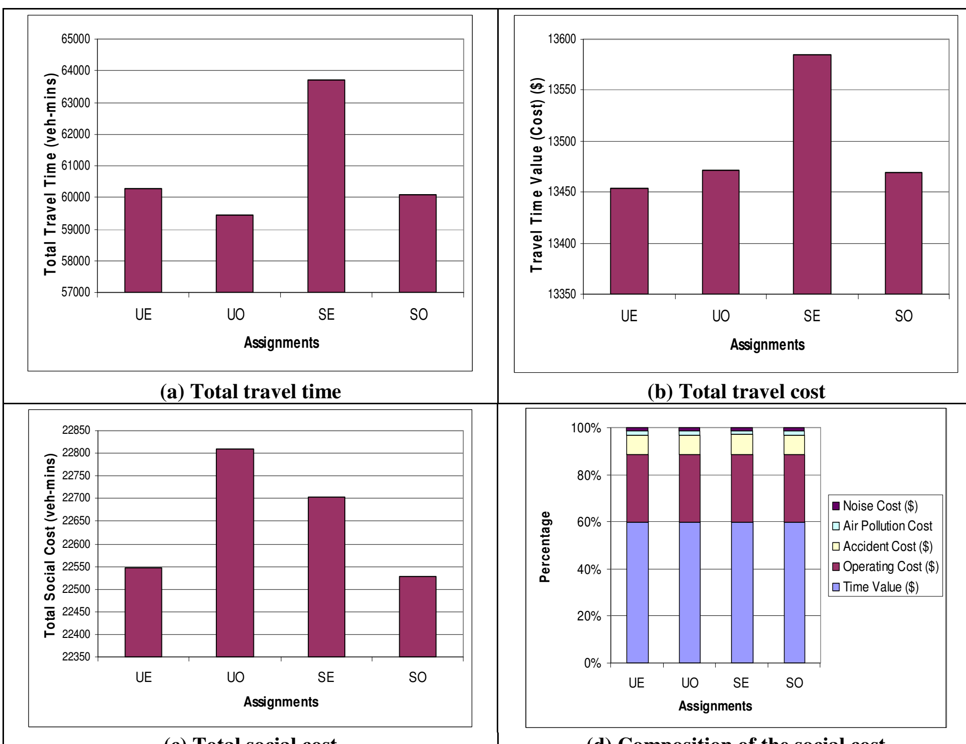
As for the value of travel time , the current travel pattern (the UE or non-interventional scenario) results in the minimum total travel value (NZ$13454). The next lowest value of travel time is for the UO (system-wide road pricing intervention). Again, the SE assignment results in the highest value of travel time, which is approximately 0.96% more than for the UE result. The SO result is also very close to the UO value. This suggests that the difference between the UO and SO assignments is mainly due to different time values in the PEM (Transfund 2002) for free flow travel time and additional travel time due to congestion. In the

PEM, travel times under un-congested and congested condition are evaluated differently (NZ$16.27/veh/hr for the former and $3.95/veh/hr for the latter).

Finally, the SO assignment provides the lowest social cost for the system (NZ$22528). The highest value occurs for the UO assignment (NZ$22809), which is approximately 1.25% more than the SO results. Also interesting to highlight is the composition of the social costs as shown in Figure 3(d), which shows virtually the same proportion of costs for all four types of assignments.

Table 2 – The results of the four assignments

	Assignment			
	UE	UO	SE	SO
Total travel time (veh-min) *(% increase from UO)*	60271 *(4.9)*	57435 *(N.A.)*	63707 *(10.9)*	60086 *(4.6)*
Total travel time value (NZ$) *(% increase from UE)*	13454 *(N.A.)*	13471 *(0.13)*	13584 *(0.96)*	13470 *(0.12)*
Total Social Cost (NZ$) *(% increase from SO)*	22547 *(0.08)*	22809 *(1.25)*	22703 *(0.78)*	22528 *(N.A.)*



(a) Total travel time **(b) Total travel cost**

(c) Total social cost **(d) Composition of the social cost**

Figure 3 – Results of the traffic assignment for the study area

3.4 Comparative Analysis

The results described in section 3.3 indicate that there is a clear relationship between network performance measures (total travel time, total travel 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). However, considering the economic value of time (total travel cost), the benefits of road pricing are actually negative, as implementation of road pricing (UO) increases the total travel time value by $17 from the UE assignment results. Furthermore, using the total social cost as the performance measure leads to the conclusion that a road pricing scheme (UO) would be the worst possible policy.

Consequently, it appears that totally different decision outcomes are generated 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, will lead to a decision that at the same time disregard the economic feasibility and the social impacts. As shown in Figure 4, 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 the worst option. 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 without any consideration to the external cost they generate to society.

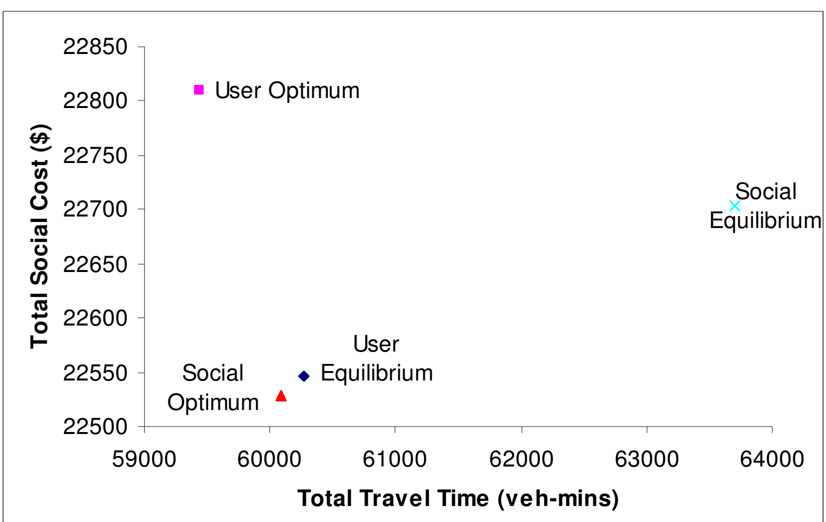


Figure 4 – Comparative analysis of the assignments

5. 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 do 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 not reliably predicted. 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 road charging may create negative benefits for society. In addition, the main purpose (increasing transportation efficiency) is not served well, since one of the consequences is an increase in the total travel time cost. In other words, road pricing to save travel time may bring economic inefficiency (i.e. it may have negative benefits when the cost function changes from the absolute time to the time value or social cost).

There is a dilemma in that these three 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, two main directions can be highlighted. Firstly, it would be important and interesting to conduct similar analyses on larger and more congested urban networks, to identify the transferability of the findings in this paper. The road network in the study is very limited and the paradoxical effects resulting from the different assignments (UE, UO, SE and SO) may assume other dimensions of complexity. Secondly, 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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