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A Multimodal Multiuser Approach for Analysing Pricing Policies in Urban Contexts

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Abstract: In recent years several European cities have introduced road pricing as a tool for managing transport demand, especially to reduce traffic congestion and rebalance the modal split between private vehicles and mass-transit systems. Indeed, user behaviour brings about a User Equilibrium condition, which does not correspond to overall utility maximisation and fails to take account of external costs. Hence, in order to achieve the efficient use of transportation systems (System Equilibrium), tolls can be charged on urban roads so that the social surplus is maximised. For several reasons (theoretical, political, social acceptability) it is impossible to charge efficient tolls (first-best solutions) proposed in the literature; therefore in real networks sub-optimal tolls (second-best solutions) are applied. In this study we analyse the effects on optimal fare design when pricing revenues are wholly or partly used for improving public transport. In particular, we formulate a model according to economic theory in a multimodal and multiuser context, where multimodal features are calculated explicitly on the network for each fare configuration. The model is applied on a trial network (built with heterogeneous values of relative accessibility among different traffic zones) and several second-best strategies are analysed with particular attention to the use of pricing revenue.

Key words: System equilibrium, pricing policies, second-best tolls

INTRODUCTION

Road pricing is currently considered one of the most powerful tools for managing transport demand in urban areas. In recent years several European cities (such as London, Stockholm and Milan) have introduced road pricing as a travel demand management strategy. Many reasons, such as congestion, noise and air pollution reduction, lead public administrations to use pricing policies in urban contexts. These measures allow transportation systems to be managed more efficiently and sustainably since they can generally yield a temporal, spatial and modal redistribution of travel and particularly rebalance the modal split between private vehicles and mass-transit systems. In a transportation network, the natural interaction between mobility demand and transportation supply leads the transportation system to a condition defined as User Equilibrium (UE). In a simple case of one origin-destination pair connected by one link, user equilibrium can be graphically represented by the intersection between the demand function and the supply function, as shown in Fig. 1. The UE condition is known to be non-efficient in economic terms, where efficiency

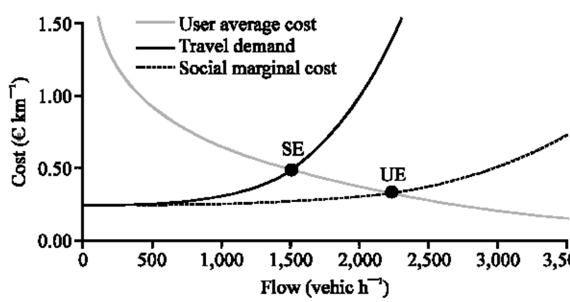

Fig. 1: User Equilibrium (UE) and System Equilibrium (SE) conditions

entails total cost minimization, in the rigid demand case and in terms of user surplus maximisation, in the elastic demand case (Beckmann *et al*., 1956). This condition is known as System Optimum (SO) when the deterministic approach is used to solve the network assignment problem and System Equilibrium (SE) (Gentile *et al*., 2005) or Stochastic System Optimum (SSO) (Stewart, 2007) when the user choice model is a random utility model. As shown in Fig. 1, the SE condition can be graphically represented by the intersection between the demand function and

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marginal cost function (indicated in the literature also as social cost or marginal social cost function). This function is equal to the individual cost plus the additional cost incurred by all other vehicles when one extra vehicle is on the road. The discrepancy between the User Equilibrium and the System Equilibrium comes from user behaviour in making mobility choices: an additional user, entering a traffic flow, considers a travel cost that does not include the cost increase imposed on the other travellers in the network. In other words, travellers try to maximise their own utility or private benefits instead of considering social welfare. It is shown that efficient transportation system use can be achieved by charging efficient tolls on network links. The optimal situation can be reached by the imposition of a tax (or toll) that will reconcile the private cost and the social cost (Prudhomme and Bocarejo, 2005). These tolls, called Marginal Social Cost Pricing (MSCP) tolls, are equal to negative externalities (such as congestion cost, travel delays, air pollution, accidents) imposed on other travellers by an additional user and are one of the most popular tools for road pricing applications (Yildirim and Hearn, 2005). According to Marginal Social Cost (MSC) theory, many advanced models are formulated to design pricing strategies (Yang and Huang, 2004; Hamdouch *et al*., 2007; Kuwahara, 2007). Generally in the economic literature a condition where all tolls are equal to marginal external costs on each link is referred to as the first-best condition. However, it is not always possible to determine the optimal fare for one good because of the distortions in the market for related goods (Rouwendal and Veroef, 2006).

Hence in this case we consider sub-optimal solutions (second-best tolls) in which not all links are tolled. The second-best tolls issue has been extensively studied (Verhoef *et al*., 1996; Lawphongpanich and Hearn, 2004; Zhang and Ge, 2004; Ekstrom *et al*., 2009). First best tolls are achieved only in a theoretical condition for mobility demand segmentation: for instance, users can differ from each other with respect to the Value Of Time (VOT). Several authors have studied the anonymous tolls problems (Arnott and Krauss, 1998; Yang and Zhang, 2008). Furthermore, there are several practical reasons why transport regulators often consider second-best solutions: capital and monitoring costs may be prohibitive or they may prefer to start with a demonstration project before implementing road pricing on a system-wide scale (Verhoef, 2002). When pricing strategies are applied in a real network, a more important issue for policy makers is what to do with road pricing revenues. Investment in public transport is generally one of the preferred options for the allocation of revenues (Farrel and Salesh, 2005). This option is chosen when the aim of pricing strategies is congestion reduction. Further, investment in public transport can reduce acceptance problems. Moreover, as stated by Kottenhoff and Freij (2009), the use of pricing revenue for improving public transport is required in order to increase the elasticity of road system users (who generally tend to keep their modal choices unchanged) and compensate for a decrease in service quality due to the increase in crowding of public transport vehicles.

However, it is worth noting that the improvement in public transport should be implemented before or simultaneously with pricing policy application in order to avoid the above-mentioned problems. Indeed, four months before the beginning of the Stockholm congestion charging trial the public transport services were extended by 7% (Eliasson *et al*., 2009). Likewise, when the Ecopass System was implemented in Milan, the bus service improved by 16% (Municipality of Milan, 2009).

In Norway, tolls are used to finance both urban and inter-urban road projects. In the three largest cities of Oslo, Bergen and Trondheim cordon tolls make up the main funding of road investments and, to a certain extent, public transport investment programmes (Odeck and Brathen, 2008). As part of the revenues are used for the pricing system operating costs, the revenue rate that can be allocated to public transport improvement depends on the toll collection system adopted. In other words, if we consider the Oslo Toll Ring, an electronic cordon pricing scheme, operational costs are only 10% of the total revenue (Ieromonachou *et al*., 2007). Instead, if we consider London Congestion Charging, an area pricing scheme with no electronic system for toll collection, for the financial year 2007/2008 total costs (scheme operation, publicity, enforcement, Transport for London staff, traffic management, Transport for London central costs) were £131 million and total revenues (daily vehicle charges, enforcement income received) were £268 million (TFL, 2008), making operational costs for London Congestion Charging 49% of total revenue. Obviously, it is impossible to compare the Oslo Toll Ring and London Congestion Charge because their aims are very different (to provide investments for transport programmes, in the first case and to reduce congestion, in the second). It is important to note that the revenue rate available can vary greatly according to the toll collection system.

In this study we provide an analysis of the fare definition problem when part of pricing revenues are used for improving public transport. Indeed, a multimodal approach in the toll computation model is generally adopted, neglecting revenue use (Gentile *et al*., 2005) or calculating fares in the case of homogeneous networks (Huang, 2002; Ferrari, 2005). Therefore, we formulate a toll computation model through a multidimensional constrained optimisation problem in multimodal and multiuser context with elastic demand. This model is then applied on a heterogeneous (i.e., any origin-destination pair has different accessibility) trial network to analyse several second-best strategies (such as cordon and parking pricing) and estimate possible effects of road pricing revenue use on social welfare and fare levels.

TOLL COMPUTATION MODEL AND ALGORITHM

In the literature (Cascetta, 2001), a transportation network can be modelled by means of graph theory: a graph can be defined as an ordered pair of sets N and L, where N is the set of elements indicated as nodes and L is a set of pairs of nodes belonging to N indicated as links.

Links of a graph in a transportation network represent trip phases, such as physical movements on a road or train waiting at a station. Likewise, nodes of a graph describe the transition among trip phases (i.e., links), such as vehicles that pass through an intersection. Moreover, it is necessary to associate to each link: an impedance function and a flow value. Impedance functions, known as cost functions represent the resource consumption associated to the link crossing; flow values indicate the average number of users or vehicles which, in a unit of time, cross the considered links.

In a transportation network, there is a peculiar class of nodes associated to each traffic zone (a portion of territory in which the analysed area is divided) indicated as centroid nodes that represent the origin and/or destination of all trips related to the considered zone. Finally, a path can be defined as a sequence of successive links connecting an origin centroid node with a destination centroid node, where each origin-destination pair can be connected by means of more than one single path.

In order to model effects of the transportation system on people choices, it is necessary to divide the population into user classes, where each class represents a homogeneous category with respect to socio-economic features, such as car availability or income levels.

The User Equilibrium (UE) condition, that is the network configuration resulting from the interaction between people preferences and transportation system performance, can be formulated mathematically through the interaction between two kinds of models: supply models, that simulate the performance of transportation systems depending on user (or vehicle) flows and demand models, that imitate user choices influenced by transportation system performance. A supply model can be summarised by the following analytical relation:

$$C_m^{i,h} = A_m{}^T c_m^{i,h}\left(f_1^h,\ldots,f_m^h,\ldots,f_n^h\right) + C_{m,i,h}^{NA} \tag{1}$$

where: $C_m{}^{i,h}$ is the vector of path generalised costs for user class i and mode m (such as car or bus) at time period h, of dimensions ($n_{m\text{-Paths}} \times 1$), whose generic element $C_{m,i}^{k,h}$ expresses the generalised cost of path k for user class i on mode m at time period h; A_m is the link-path incidence matrix for mode m, of dimensions ($n_{m\text{-Links}} \times n_{m\text{-Paths}}$), whose generic element $a_{l,k}{}^m$ = 1 if link l belongs to path k, 0 otherwise; $c_m{}^{i,h}$ is the vector of link generalised costs for user class i and mode m at time period h, of dimensions ($n_{m\text{-Links}} \times 1$), whose generic element $c_l^{m,i,h}$ expresses the average cost perceived by users of class i when they pass through link l of mode m at time period h (in a congested network this vector depends on total link flows $f^h{}_m$ of mode m at time period h); $f_m^h = \sum_i f_m^{i,h}$ is the vector of link flows of mode m at time period h, of dimensions ($n_{m\text{-Links}} \times 1$), whose generic element $f_l^{m,h}$ expresses the average number of travellers that pass through link l on mode m in a time unit during time period h, which is equal to the sum of flow vectors $f_m{}^{i,h}$ related to each user class i, of dimensions ($n_{m\text{-Links}} \times 1$), whose generic element $f_l^{m,i,h}$ expresses the average number of class i users that pass through link l on mode m in a time unit during time period h; $C_{m,i,h}^{NA}$ is the vector of non-additive path costs for user class I and mode m at time period h, of dimensions ($n_{m\text{-Paths}} \times 1$), whose generic element $C_{k,h}^{m,i,NA}$ expresses costs that depend only on path k of mode m for user class i at time period h (such as road tolls at motorway entrance/exit points).

The demand model can be defined as a mathematical relationship that associates average demand flows to a given activity and transportation supply systems. Travel demand models are usually derived from random utility theory based on the hypothesis that every user is a rational decision-maker maximising utility relative to his/her choice (Cascetta, 2001). Generally the utility associated to each travel choice is a linear function of generalised travel cost. The demand model can be described by the following mathematical relation:

$$\begin{aligned} f_m^{i,h} = A_m\, F_m^{i,h} = A_m\, P_m^{i,h}\left(-C_m^{i,h}\right) d_m^{i,h}\, \big(&C_1^{1,h},\ldots,C_1^{i,h},\ldots C_1^{g,h},\ldots, \\ &C_m^{1,h},\ldots,C_m^{i,h},\ldots,C_m^{g,h},\ldots,C_n^{1,h},\ldots C_n^{i,h},\ldots,C_n^{g,h}\big) \end{aligned} \tag{2}$$

where, $F_m{}^{i,h}$ is the vector of path flows for user class i and mode m at time period h, of dimensions ($n_{m\text{-Paths}} \times 1$), whose generic element $F_k{}^{m,i,h}$ expresses the average number of class i users that choose path k of mode m in a time unit during time period h; $P_m{}^{i,h}$ is the path choice probability matrix for user class i and mode m at time period h, known as the path choice map, of dimensions ($n_{m\text{-Paths}} \times n_{OD\text{-Pairs}}$), whose generic element $p_{k,od}^{m,i,h}$ expresses the probability that class i users travelling between origin-destination pair od choose path k of mode m at time period h, which generally depends on path generalised cost matrix $C_m^{i,h}$; $d_m^{i,h}$ is the travel demand vector for user class i and mode m at time period h, of dimensions ($n_{OD\text{-}Pairs} \times 1$), whose generic element $d_{od}^{m,i,h}$ expresses the average number of class i users travelling between origin-destination pair od on mode m in a time unit during time period h. If travel demand is assumed elastic, vector $d_m^{i,h}$ depends on path cost vectors $C_m^{i,h}$; otherwise it is fixed.

Combining Eq. 1 with 2, we obtain the well-known assignment model formulated as a fixed-point model (Cantarella, 1997):

$$\begin{aligned}\bar{f}_m^{i,h} = \sum_i \bar{f}_m^{i,h} = \sum_i A_m\, P_m^{i,h}\Big(&-A_m{}^T c_m^{i,h}\big(\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) - C_{m,i,h}^{NA}\Big)\\ d_m^{i,h}\Big(&-A_1{}^T c_1^{1,h}\big(\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) - C_{1,1,h}^{NA},\ldots,\\ &-A_m{}^T c_m^{i,h}\big(\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) - C_{m,i,h}^{NA},\ldots,\\ &-A_n{}^T c_n^{g,h}\big(\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) - C_{n,g,h}^{NA}\Big)\end{aligned}$$

where: $\bar{f}_m^h$ is the vector of link flows for mode m in the UE condition at time period h; $\bar{f}_m^{i,h}$ is the vector of link flows of user class i for mode m in the UE condition at time period h.

Because the UE condition is not efficient from an economic point of view, tolls need to be charged to affect user behaviour in order to achieve the best utilisation of the transportation system. Since there are two kinds of user costs, additive and non-additive (as shown in Eq. 1), we need to introduce two kinds of fares: additive (indicated as y) and non-additive (indicated as Y). Formally, non-additive fares have to be considered as path fares. Such tolls are applied to groups of paths that satisfy several conditions (such as all paths that join the same origin-destination pair). Thus, the real number of variables to be optimised is lower (indeed, we need a variable for each group) and it is not necessary to explicitly enumerate all considered paths (path enumeration is generally performed implicitly by the assignment algorithm). An example of an additive fare is the toll that depends on the length of the link (if a car crosses two links it will pay a fare equal to the sum of the two corresponding tolls), while an example of a non-additive fare is parking pricing because it depends only on the place where users park and parking duration and does not depend on the number (or length) of crossed links to reach one's destination.

Moreover, if we consider a fixed policy (i.e., the fare does not depend on the time spent in the system), variables y and Y represent the fare value, while if we consider hourly policies (i.e., fares depend on the time spent in the system, such as parking fares), variables y and Y represent the cost per unit time and the corresponding value for each user can be obtained by multiplying these values by the time spent in the system.

Toll determination can be formulated as a multidimensional constrained optimisation problem which, according to economic theory, consists in finding out the fare values $\hat{y}$ and $\hat{Y}$ which maximise the social surplus (the opposite of objective function Z), that is:

$$\left[\hat{y},\hat{Y}\right] = \underset{y\in S_y\,;\,Y\in S_Y}{\arg\min}\; Z\big(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) \tag{3}$$

subject to:

$$\left[\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right] = \Lambda\big(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\big) \tag{4}$$

$$f_m^h \in S_{f_m} \qquad \forall m \in \{1,\ldots,n\} \tag{5}$$

where: y is the vector of additive fares, of dimensions ($n_{Road\text{-}Links} \times 1$), whose generic element y_l represents the value of pricing applied to link l; Y is the vector of non-additive fares, of dimensions ($n_{Road\text{-}Paths} \times 1$), whose generic element Y_k represents the value of pricing applied to path k; $\hat{y}$ [$\hat{Y}$] is the optimal value of vector y [vector Y]; S_y [S_Y] is the feasibility set of vector y [vector Y], which expresses minimum and maximum value for each additive [non-additive] fare; Z is the objective function to be minimised, which is equal to the opposite of social surplus; Λ is the assignment function; S_{f_m} is the feasibility set of link flows of mode m, which expresses flow consistency (for instance, the sum of all incoming flows in a node has to be equal to the sum of all outgoing flows if the node is not a centroid).

The first constraint (Eq. 4) represents the multimodal assignment constraint that provides user flows on all transportation systems ($\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h$) as a function of design variables (y and Y) and user flows on all transportation systems ($\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h$). However, it is worth noting that with respect to the multimodal assignment model proposed in the literature in this case we also take into account the crossed congestion phenomenon, that is an increase in flows on the road system provides an increase in travel times also for public transport if operating on shared links. This assumption introduces some theoretical complications because it does not satisfy some assumptions proposed by Cantarella (1997) for stating the uniqueness of the equilibrium solution in the case of multimodal approaches. Instead, the second constraint (Eq. 5) indicates that flows have to satisfy consistency conditions (as indicated in the definition of set S_{f_m}). The objective function Z is assumed equal to the opposite of social surplus and can be expressed as the sum of User Surplus (US), Traffic Revenues (TR), System Costs (SC) and Environmental Costs (EC):

$$\begin{aligned}&Z\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)=-US\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)\\&-TR\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)+SC\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)\\&+EC\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)\end{aligned} \tag{6}$$

The US can be used as an indicator of transportation user welfare. It thus represents the net utility that users obtain by making travel choices and equals the average maximum perceived utility in a stochastic approach, that is the EMPU (Expected Maximum Perceived Utility) variable. The Logit model used for modal split allows the EMPU variable to be expressed in closed form as indicated by the following relation:

$$US\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)=\sum_h\sum_{od}\sum_i\left(d_{od}^{i,h}\right)\cdot W_{od}^{i,h}\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right) \tag{7}$$

where: $d_{od}^{i,h}$ is the travel demand on pair o-d related to user class i at time period h; $W_{od}^{i,h}$ is the EMPU variable, calculable with the well-known formula:

$$W_{od}^{i,h}=\vartheta\ln\sum_m\exp\left(V_{m,od}^{i,h}/\vartheta\right)$$

in which $V_{m,od}^{i,h}$ is the systematic utility that users of class i associate to mode m on pair o-d at time period h and ϑ is the Logit parameter.

The second and third terms in the social surplus expression are the amount of traffic revenues, provided by public and private systems and the amount of system costs, respectively. The latter term is the sum of the operating costs of the transit system, that are a function of performance parameters and the operating costs of the pricing system, assumed constant with respect to network flows:

$$\begin{aligned}&TR\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)=\sum_h\sum_m y^T\cdot\bar{f}_m^h\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)\\&+\sum_h\sum_m Y^T\cdot\bar{F}_m^h\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)\end{aligned} \tag{8}$$

where $\bar{F}_m^h$ is the path flow vector in equilibrium condition for each user class i and each mode m at time period h, of dimensions ($n_{m\text{-Paths}}$ ×1), whose generic element $F_k^{m,h}$ expresses the average number of travellers that choose path k on mode m in a time unit during time period h; this vector is equal to $\bar{F}_m^h=\sum_i F_m^{i,h}$

$$SC\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)=OCTS(PPTS)+OCPS \tag{9}$$

where: OCMT are the operating costs of the mass transit system, depending on performance parameters of the mass transit system (PPTS); OCPS are the operating costs of the pricing system, that are constant with respect to network flows and variable according to the toll collection system.

The last term is the amount of external costs, which are expressed in the literature as a function of equilibrium flows, that is:

$$EC\left(y,Y,\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right)=EC^*\left(\bar{f}_1^h,\ldots,\bar{f}_m^h,\ldots,\bar{f}_n^h\right) \tag{10}$$

In order to solve the optimisation problem (3) we have adopted the meta-heuristic algorithm proposed by D'Acierno *et al*. (2006). This algorithm is based on three steps: an Exhaustive Mono-dimensional Optimisation (EMO) phase; a Starting Solution Definition (SDD) phase and a Neighbourhood Search Optimisation (NSO) phase.

In the first phase, each variable is optimised exhaustively, assuming the values of other variables as constant. Phase 2 is obtained by setting each variable equal to the optimal value calculated in the previous phase. Finally, the last phase evaluates the solutions that can be obtained from the current solution by an elementary move (i.e., only one variable is increased or decreased while the other variables are maintained constant) and identifies a new solution to be analysed.

This meta-heuristic algorithm was adapted in order to manage the peculiar design variable framework (variables y and Y) that, is different from the optimisation model proposed by D'Acierno *et al*. (2006). Characterisation of the variables is given in the following section.

TRIAL NETWORK APPLICATION

The model formulated in the previous section was applied on a trial network to verify the efficiency of several pricing policies. The trial network is shown in Fig. 2. Network users can choose among three transport modes: car, transit and pedestrian. However, the accessibility variable is the main network feature, according to a real network of a large metropolitan area: for instance, between node 4 and node 2 there is no transit system that joins this pair directly. For the demand, we considered three user classes that differ in modal choice set and parking time: users who have no car availability (10% of total demand for each O-D pair), users who have car availability and have to stay at their destination for 2 h (20% of total demand for each O-D pair) and users who have car availability and have to stay at their destination for 6 hours (70% of total demand for each O-D pair). The demand for each O-D pair is such as to produce high congestion levels in the network when no pricing policy is applied.

Only second-best policies were tested. We applied cordon pricing and some parking pricing policies: a parking policy with undifferentiated fares (in each zone the same fare is applied), a destination-based parking policy (the traditional strategy where road users pay for parking and the fare is a function of where they park) and an Origin-Destination (OD) parking policy, that is a strategy proposed by D'Acierno *et al*. (2006) where road users pay a fare based on both trip origin and destination. All proposed parking strategies have been applied in two cases: the case of fixed fares (in this case variables y and Y express the fare value) and the case of hourly fares (in this case variables y and Y express the fare per unit time and the corresponding value for each user can be obtained by multiplying these values by the parking time). Obviously, in the case of cordon pricing policy the fare can be only fixed (indeed, the application of an hourly cordon pricing policy would require the implementation of advanced technologies able to calculate the time spent by each vehicle in the charging area). Furthermore, for each policy we considered different applications related to the use of pricing revenue for improving public transport. In particular, we considered five use schemes: pricing revenues not used, 25% of pricing revenues used, 50% of pricing revenues used, 75% of pricing revenues used and 100% of pricing revenues used.

However, it is worth noting that, in real contexts, the percentage of pricing revenues which can be used to improve other transportation systems (such as public transport) depends on operating costs of the pricing system. For instance, when a cordon pricing strategy with electronic toll collection system is implemented, operating costs can be very low such as in the Oslo Toll Rings system (Ieromonachou *et al*., 2007), such that there is a considerable availability of money to finance other projects or systems. On the contrary, in parking strategies, it could be difficult to use a fully electronic collection system (except in restricted areas such as controlled parking lots) because ticket inspections would require physical inspection by traffic policeman or other operators with the consequent increase in operating costs. Therefore, for parking strategies the percentage of revenues which can be used for improving public transport is seldom higher than 50%.

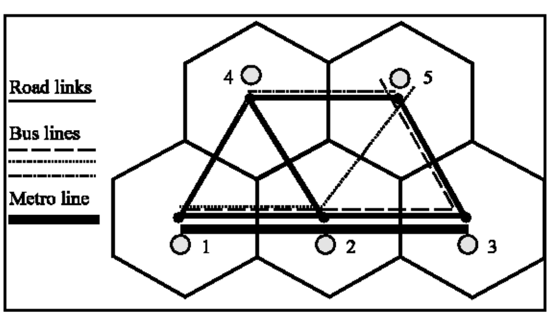

Fig. 2: Trial network scheme (D'Acierno *et al*., 2006)

Although the trial network is the same as that reported by D'Acierno *et al*. (2006), in this case some modifications to the algorithm framework were applied. In particular, the optimisation model proposed by D'Acierno *et al*. (2006) designed only hourly parking fares. In our application we considered both fixed parking fares (in this case design variables represent the real value of the fare and not the fare per time unit) and cordon pricing fares (in this case the elements of variable Y are equal to zero if the destination of the path is a non-cordoned area and equal to the pricing value if the destination is the cordoned area). Moreover, the solution algorithm was modified to take account of multimodal effects in terms of user flows on different transportation systems due to the use of a share of pricing revenues for improving public transport.

Figure 3-7 show optimisation results for each pricing policy with different percentages of revenue used for improving public transport. In particular in each figure, the value of the objective function is provided, expressed in its Euro equivalent (i.e., travel times are expressed in euros by means of value of time coefficients) per hour.

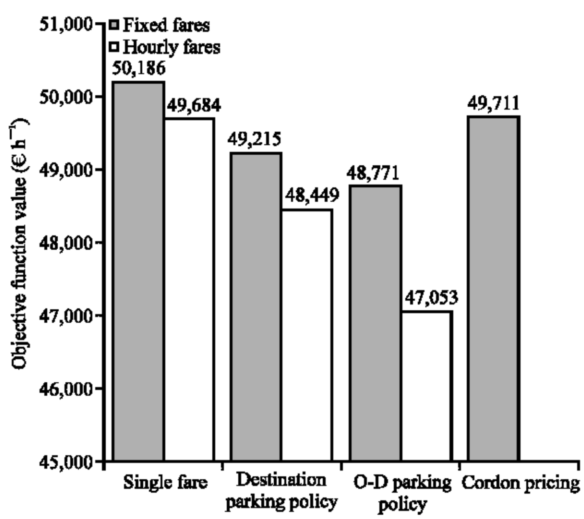

Fig. 3: Objective function value when pricing revenues are not utilised

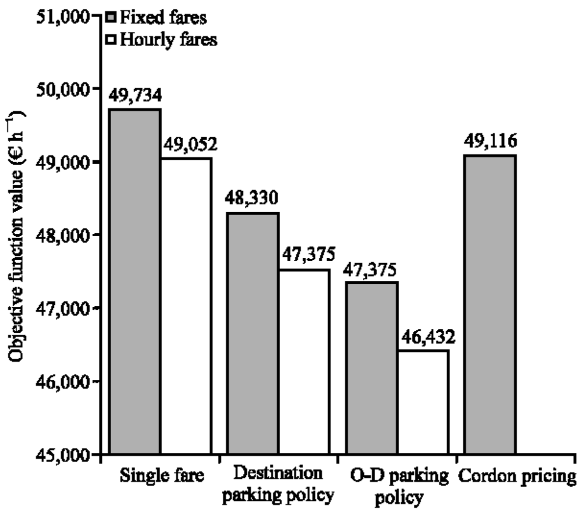

Fig. 4: Objective function value when 25% of pricing revenues are utilised for improving public transport

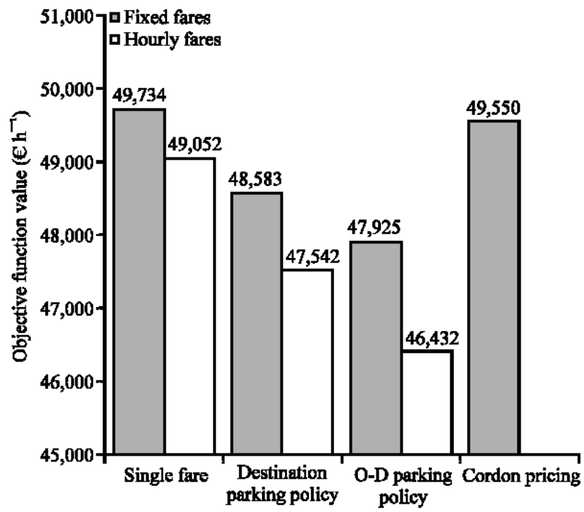

Fig. 6: Objective function value when 75% of pricing revenues are utilised for improving public transport

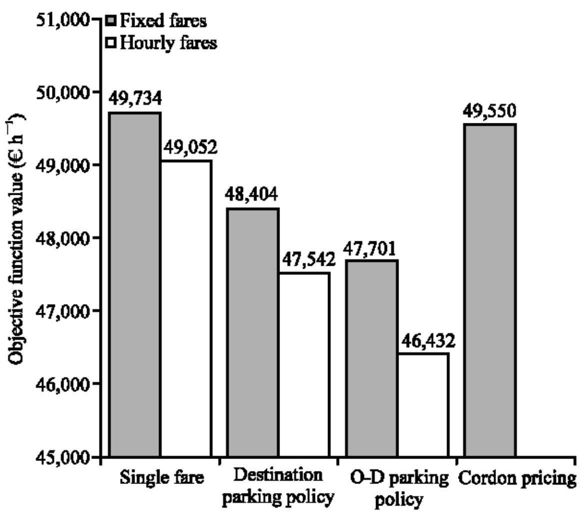

Fig. 5: Objective function value when 50% of pricing revenues are utilised for improving public transport

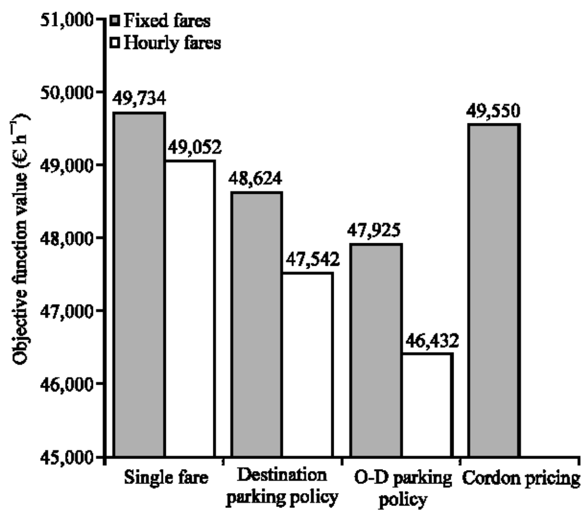

Fig. 7: Objective function value when 100% of pricing revenues are utilised for improving public transport

It is worth noting that in any case pricing policies with hourly fares (and with any percentage of revenue used to improve public transport) are always better than cordon pricing. Moreover, the best policy seems to be the parking one based on origin-destination fares.

Figure 8 provides a comparison among the analysed strategies (both in terms of fixed and hourly fares) in the case of different percentages of pricing revenues used to improve public transport. The main result is that the best value of the objective function can be found for any strategy in the case of between 25 and 50% revenue used. The reason for this result is related to the fact that in the case of values lower than 25% the increase in public transport performance can be neglected, while in the case of values higher than 50% the great attractiveness of public transport over the private system provides a reduction in pricing revenues and therefore the amount of resources available for public transport. Hence the system reaches an optimal configuration that represents a compromise between the need to reduce the number of car users and the fact that they themselves are implicitly the main backers of public transport.

Analysis of the modal split (Fig. 9-13) shows that hourly fares always provide higher travel demand for public transport and the strategy that provides the highest value of public transport use is always parking pricing based on both trip origin and destination. With respect to revenue use, for values greater than 25% the modal split values are constant because the system achieves an equilibrium condition related to the reduction in public transport backers.

Generally, the adopted objective function does not provide a maximisation of public transport demand but the joint maximisation of revenues and accessibility. Indeed, modal splits indicated in Fig. 9-13 represent the average values on the network without taking into account different levels of accessibility of each origin destination pair. Therefore, the adopted objective function (described in Eq. 6), which allows to take into account the maximisation of relative accessibility of each origin destination pair, can be considered a good tool for design transportation systems.

Finally, it may be shown that revenue use for increasing service frequencies allows fare levels to be decreased, where this reduction depends on performance parameters of bus system. Figure 14 describes these features comparing the cordon pricing strategy in two cases: the use of 50% of revenues for improving public transport and the lack of revenue use. To give details, we have provided the fare variation with respect to initial service frequency of bus lines in the cordon pricing case. The service frequency is supposed equal for three bus lines of the trial network. The fare reduction due to pricing revenues increases as the initial service frequency increases. From an economic standpoint, the revenue use is positive, because the social surplus improves and the fares can be reduced, thereby also gaining public opinion acceptability. Thus we can say that a well-designed parking policy can be more effective as a travel demand management instrument than a policy which charges

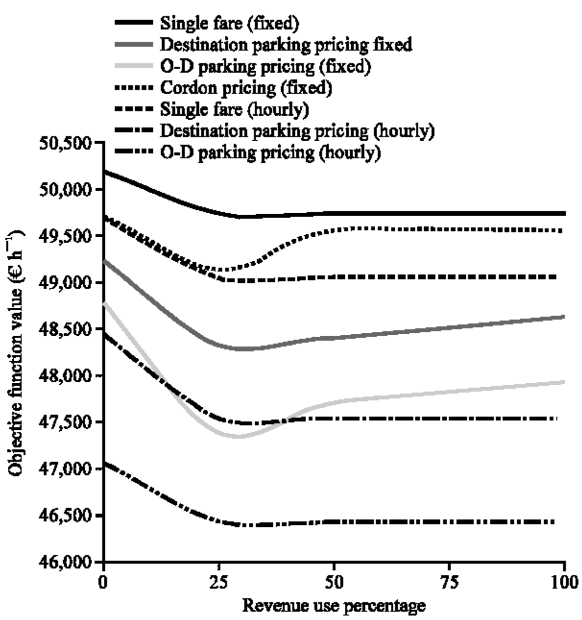

Fig. 8: Objective function value for different pricing policies and different percentage of pricing revenue use

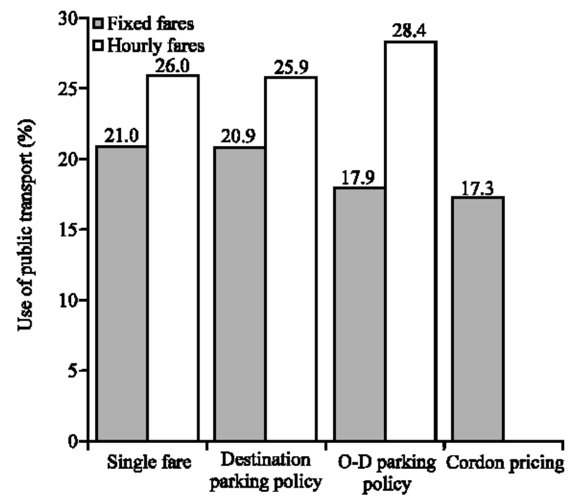

Fig. 9: Public transport demand when pricing revenues are not used

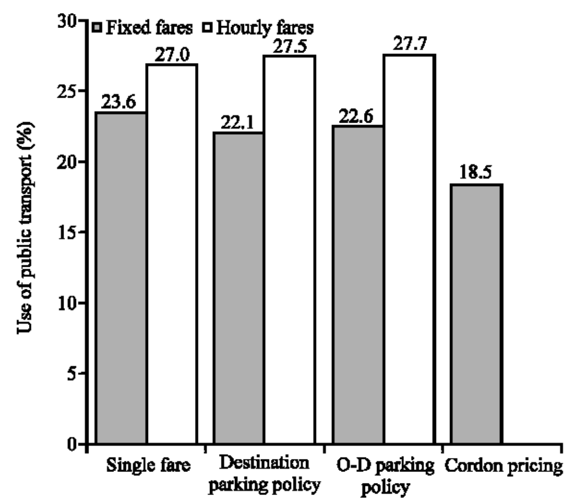

Fig. 10: Public transport demand when 25% of pricing revenues are utilised for improving public transport

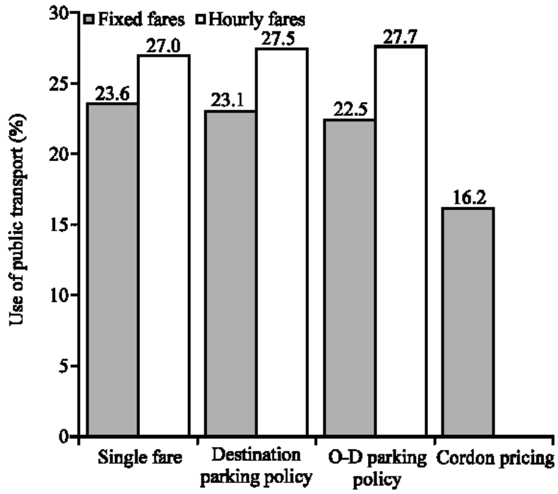

Fig. 11: Public transport demand when 50% of pricing revenues are utilised for improving public transport

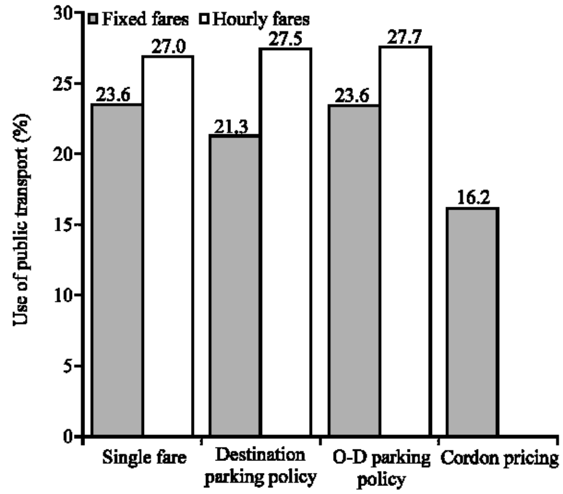

Fig. 13: Public transport demand when 100% of pricing revenues are utilised for improving public transport

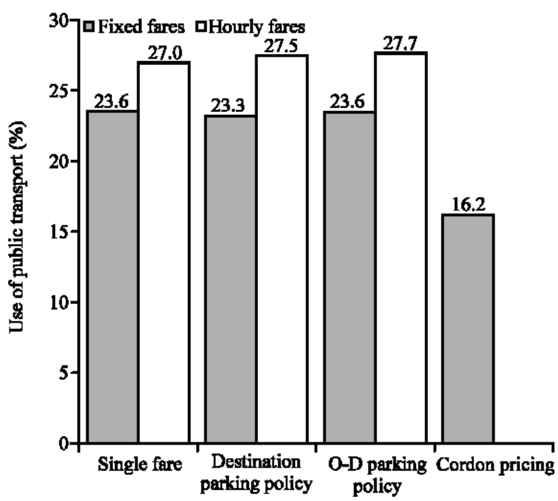

Fig. 12: Public transport demand when 75% of pricing revenues are utilised for improving public transport

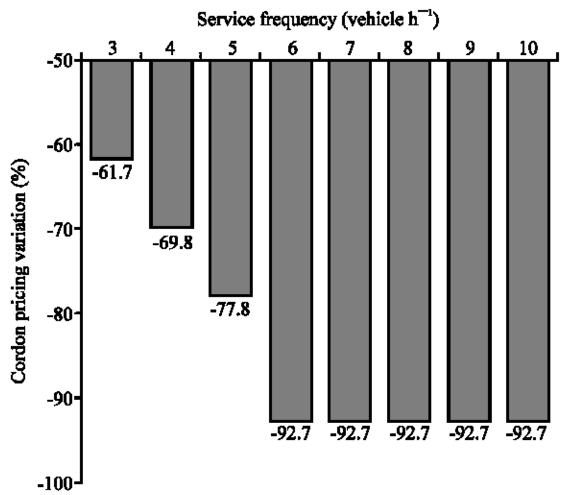

Fig. 14: Fare reduction obtained when 50% of pricing revenues are utilised for improving public transport

users a toll to reach the city centre. Revenue use is to be preferred because the social surplus increases and fares can be reduced.

According to economic theory (Pigou, 1920; Beckmann *et al*., 1956) the best utilisation of a transport system can be achieved by charging each user with an additional cost equal to the difference between the marginal cost and the individual average cost. Since users generally have different socio-economic features, their individual average cost could be different. Hence, the best strategy to be adopted is the one that allows different (socio-economic) classes of users to be charged different fares. In our trial network the main differences between users is car availability and parking time at destination. Therefore, in this case, the best strategy (i.e., the strategy that allows different fare levels to be applied according to class features) is hourly parking pricing based on the origin-destination of trips since it only charges car users a fare depending on their parking times.

CONCLUSIONS AND RESEARCH PROSPECTS

In this study we formulated a toll computation model according to economic theory of efficient tolls that can be charged on road links to achieve the best use of a transportation network. Since for several reasons theoretical tolls are impossible to apply, we analysed the effectiveness of some second-best policies, such as cordon and parking pricing, through the application of the formulated model on a trial network. In line with a real network in a large metropolitan area, we used a multimodal network with variable accessibility among Origin-Destination pairs and mobility demand segmented according to socio-economic features. In particular, if we consider users with different parking times, road pricing may not be the best strategy, while a parking pricing policy, such as an Origin-Destination (OD) parking policy, may prove more effective as a mobility management instrument. Furthermore, a parking pricing policy involves fewer unacceptable problems than a road pricing policy, which hardly ever meets the approval of both public opinion and political decision-makers. As many authors suggest, the revenue use for public transport improvement is positive, because not only does the social surplus value improve but fares can also be reduced, thus also gaining public opinion acceptability. Obviously, these considerations on the effectiveness of the examined pricing policies are related to the features of the analysed trial network. In a future project, we propose to analyse these conditions on a real network to explore the problem of the revenue percentage to be utilised, since current indications show that the percentage is variable and depends on the toll collection system adopted.

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