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# **An influence of road pricing upon the provision of bus transit services in Oslo**

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## **Abstract**

Discussions of road pricing have paid relatively small attention to the potential effects on the provision of public transport services in a region as depending upon the level of competition in a public transit sector. The present paper uses a fairly simple transport network equilibrium model of the greater Oslo region of Norway in order to investigate the impacts of road pricing upon the performance of bus transit sector. Empirical analysis is performed for the case of publicly and privately owned bus transit including the cases of monopoly, oligopoly and perfect competition. Analysis performed in the paper captures the present state of bus transit in the greater Oslo region as well as its possible future developments.

## **1. Introduction**

The concept of marginal social cost pricing has been introduced by Pigou (1920) and Knight (1924) and is based on the idea that people tend to do socially optimal choices in case when they face all social benefits or costs of their actions. One of the most interesting applications of this concept is the mechanism of congestion pricing advocated by William Vickrey. Vickrey (1963) demonstrate that congestion pricing influences mode and route choices of the network users as well as land use patterns. His work makes it clear that optimal toll charges should vary with time, location, vehicle type and current situation on the roads in order to match the level of congestion. Despite the elegance of congestion pricing concept,

it is found quite difficult to implement due to the existence of technological, legal, organisational, political and acceptability barriers. Nevertheless, a number of applications exist and is slowly growing. The present congestion pricing schemes include Singapore's toll system, Scandinavian toll-rings, Californian pay-lanes and recent London's toll system (see Gómez-Ibáñez and Small, 1994 and Small and Gómez-Ibáñez, 1998).

Despite the growing interest in the economic literature towards the effects of congestion pricing, just several authors have paid attention to its effects upon the public transit. Vilton (1983) suggests that the resulting equilibrium split might involve a higher share of public transit than the one prevailing before congestion pricing was introduced. This effect is investigated further by Small (2003), who splits it into the following separate parts:

- 1) Raising the monetary price of car travel induces some modal shifting to public transit.
- 2) Reduced congestion makes operating on-street transit (bus or street car) faster and cheaper.
- 3) Increased route coverage and/or service frequency to handle the demand further enhances the service quality as perceived by the user.
- 4) Higher costs of automobile commuting cause land near major business centres to become more valuable, hence, to be developed at higher residential and commercial densities. This further enhances the market potential of public

transit by increasing its density of demand in just those areas, where it is already most efficient.

Small (2003) investigates the effects of congestion pricing upon the bus transit and their contribution to the overall benefits of congestion pricing. In his analysis bus lines are publicly owned and, hence, the goal of a bus operator is to maximize aggregate consumer surplus less aggregate total cost. Given this assumption, Small demonstrates that congestion pricing can dramatically change the role of public transit, at least those modes that share the streets with private vehicles. Even without spending any of the road-pricing revenues on transit improvements, the introduction of congestion pricing leads to large increases in service and ridership, reductions in user costs and public transit fares. The welfare benefits arising from the public transit should, in principle, affect the design of road-pricing scenario.

Parry and Bento (2000) argue that since public transit is subject to increasing returns to scale, its marginal cost of supply is below the average cost. At the same time public transit operating costs are often heavily subsidised. Depending on which of these factors dominates, the public transit fare could be above or below the marginal cost of service provision. They demonstrate that in this setting, an increase in public transit demand may produce significant welfare gains or losses in the public transit market. In case when the transit fare is below marginal cost, increase in transit demand produces a welfare loss. On the other hand, when the transit fare is above marginal cost, increase in transit demand produces a welfare gains.

The present paper contributes to the existing literature by analysing the consequences of congestion road pricing upon the performance of public transit as depending upon the competitive structure of the public transit market. Analysis is performed for a particular case of bus transit market in greater Oslo region of Norway. A combined game theoretical and network equilibrium approach is used to construct a model of bus transit market equilibrium incorporating behaviour of both bus transit operators and travellers. Bus transit operators choose optimal bus fares and line frequencies base upon their marginal costs and the level of demand for bus transit services. Travellers perform mode and route choice based upon the travel costs associated with different alternatives. Equilibrium bus fares and demands levels are determined by equality between demand and supply at the market for bus transit services.

The structure of present paper may be described as follows. Section1 gives full mathematical description of the model used for an empirical analysis. Section 2 specifies initial data and describes results of the numerical simulations with the model. Section 3 presents results of the simulations and analysis their welfare implications. Section 4 concludes the paper.

## **2. The model**

In order to analyse the interactions between the bus transit operators' and the travellers' decisions, a two-part equilibrium model is formulated. The first part of the model represents demand part of the market including mode and route choices of travellers'. The second part represents supply side of the bus transit

market including oligopolistic competition between the bus operators' of the Bertrand type and their strategic decisions about the level of bus fares and frequencies at their routes.

Strategic interactions between public transit operators are modelled following the game theoretic framework of Bertrand oligopoly (Vives, 1999). This framework has been used earlier by Williams and Abdulaal (1993) in order to derive expressions for the fares and frequencies characterising Nash-Cournot equilibria between an arbitrary number of public transit operators, with the resulting profit values. This paper gives full analysis of competition strategies and the resulting market equilibrium in case of one bus line operated by several of firms. However, Williams and Abdulaal ignore the existence of rival public transit lines and the existence of network effects between public transit services in their analysis. Both these effects are rather important and are taken into account in the present paper via a network equilibrium formulation of the demand side.

The present paper develops a new type of modelling framework by integrating network equilibrium model representing demand part of the bus transit market with the oligopolistic equilibrium model representing supply part of the market. This is achieved using a Mixed Complementarity formulation of both models and linking them into a unified framework through a number of linking variables.

## 2.1. Supply side of the market

A Bertrand oligopoly model formulated in the form of Mixed Complementarity Problem (MCP) (Nagurney, 1993 and Amir and Grilo, 2003) is used in order to represent supply side of the public transit market . This part of the model derives the equilibrium number of bus operators, the level of their oligopolistic fares set by bus operators and their optimal frequencies as the functions of total demand for their services and the level of their marginal and fixed /entry costs.

Suppose that there are an equilibrium number  $\eta_r$  of firms operating the bus line  $r$ . The total demand for bus transit services on the particular line  $r$   $\Phi^r$  is divided between the operating firms according to their market shares  $\Sigma_{mr}$ , where  $m \in \{1, \dots, \eta_r\}$ . The logit demand model for bus transit services (Williams and Abdulaal, 1993) is utilised in order to derive the market shares of the firms operating the bus line  $r$  so that

$$\Sigma_{mr} = \frac{\exp(-\mu c_{mr}^{gen})}{\sum_{m'} \exp(-\mu c_{m'r}^{gen})}$$

where  $\mu$  is the scale parameter of the function and  $c_{mr}^{gen} = \varphi_{mr} + W_{mr}(g_{mr})$  is the generalised costs of using bus transit services of firm  $m$  operating the bus line  $r$ . The generalised costs consist of bus fare  $\varphi_{mr}$  charged by the operator  $m$  and waiting costs  $W_{mr}(g_{mr})$  depending upon its chosen frequency.

Each bus operator has the marginal operating costs  $MC_{mr}$  per passenger depending upon the characteristics of the line i.e. its length, number of stops etc. and fixed cost  $FC_{mr}(g_{mr})$  depending upon its frequency  $g_{mr}$ . The operators' fixed costs are associated with buying and maintaining a certain number of vehicles sufficient to support the chosen line frequency. They also include entry costs consisting of licensing fees and fees for the maintenance of road infrastructure in a region.

Given the above notation, profits of an operating firm  $m$  is equal to

$$\Pi_{mr}(\varphi_{mr}, g_{mr}) = \Phi^r \Sigma_{mr}(\varphi_{mr}, g_{mr})(\varphi_{mr} - MC_{mr}) - FC_{mr}(g_{mr})$$

Each firm operating the bus line  $r$  attempt to maximize its profits by choosing its fare and frequency levels subject to the condition that its demand does not exceed the capacity its provide, that is

$$N_r^{veh} g_{mr} - \Phi^r \Sigma_{mr}(\varphi_{mr}, g_{mr}) \leq 0$$

where  $N_r^{veh}$  is an exogenously given capacity of a vehicle. The Lagrangian of the profit maximization problem of a firm  $m$  where  $m \in \{1, \dots, \eta_r\}$  is defined by

$$L_{mr}(\varphi_{mr}, g_{mr}) = \Pi_{mr}(\varphi_{mr}, g_{mr}) + \lambda_{mr}(N_r^{veh} g_{mr} - \Phi^r \Sigma_{mr}(\varphi_{mr}, g_{mr}))$$

A model of oligopolistic competition between  $\eta_r$  firms operating the bus line  $r$  may be expressed in the form of following MCP

$$\frac{\partial L_{mr}(\varphi_{mr}, g_{mr})}{\partial \varphi_{mr}} = 0 \quad \text{for } m \in \{1, \dots, \eta_r\}$$



$$\frac{\partial L_{mr}(\varphi_{mr}, g_{mr})}{\partial g_{mr}} = 0 \quad \text{for } m \in \{1, \dots, \eta_r\}$$

$$N_r^{veh} g_{mr} - \Phi^r \Sigma_{mr}(\varphi_{mr}, g_{mr}) \geq 0 \perp \lambda_{mr} \geq 0 \quad \text{for } m \in \{1, \dots, \eta_r\}$$

This mathematical problem may be reformulated as the following oligopolistic competition model

$$\varphi_{mr} = MC_{mr} + \frac{1}{\mu(1 - \Sigma_{mr})} + \lambda_{mr}$$

$$\lambda_{mr} = \frac{1}{N_r^{veh}} \left( \Phi^r \Sigma_{mr} \frac{\partial W_{mr}}{\partial g_{mr}} + \frac{\partial FC_{mr}}{\partial g_{mr}} \right)$$

$$g_{mr} \geq \frac{1}{N_r^{veh}} \Phi^r \Sigma_{mr} \perp \lambda_{mr} \geq 0$$

Let us assume particular functional forms of the waiting costs and fixed/entry costs such that

$$W_{mr}(g_{mr}) = \frac{\theta^{time}}{2g_{mr}}$$

$$FC_{mr}(g_{mr}) = \frac{2R_r}{S_r} g_{mr} fc_{mr} + A_{mr}$$

where  $\theta^{time}$  is the monetary value of time,  $R_r$  is the length of the bus line  $r$  in km,

$S_r$  is the average speed on the bus line  $r$  in km/hour so that  $\frac{2R_r}{S_r} g_{mr}$  represent the

total number of vehicles needed to support the chosen frequency  $g_{mr}$  on the line.

$fc_{mr}$  is the fixed costs per vehicle and  $A_{mr}$  is other entry costs such as licensing costs etc.

Equilibrium fare and frequency levels corresponding these functional forms are the solution to the following MCP problem

$$\varphi_{mr} = MC_{mr} + \frac{1}{\mu(1 - \Sigma_{mr})} + \lambda_{mr}$$

$$\lambda_{mr} = \frac{1}{N_r^{veh}} \left( \frac{2R_r}{S_r} fc_{mr} - \frac{\theta^{time} S_r^2}{2\Phi^r \Sigma_{mr}} \right)$$

$$g_{mr} \geq \frac{1}{N_r^{veh}} \Phi^r \Sigma_{mr} \perp \lambda_{mr} \geq 0$$

Let us now assume that all the operating firms are identical with respect to their cost functions i.e.  $MC_{mr} = MC_r$ ,  $fc_{mr} = fc_r$  and  $A_{mr} = A_r$ . Hence, they choose the same bus fares  $\varphi_r$  and frequencies  $g_r$  and obtain equal market shares

$\Sigma_r = \frac{1}{\eta_r}$ , which result in the following oligopolistic problem

$$\varphi_{mr} = MC_{mr} + \frac{\eta_r}{\mu(\eta_r - 1)} + \lambda_r \tag{1}$$

$$\lambda_r = \frac{1}{N_r^{veh}} \left( \frac{2R_r}{S_r} fc_{mr} - \frac{\theta^{time} S_r^2 \eta_r}{2\Phi^r} \right) \tag{2}$$

$$g_{mr} \geq \frac{\eta_r}{N_r^{veh}} \Phi^r \perp \lambda_r \geq 0 \tag{3}$$

Equations (1)-(3) give complete formulation of market equilibrium for a particular bus line  $r$  for a given number of operating firms  $\eta_r$  and given level of bus transit demand.

## **2.2. Demand side of the market**

Mode and route choices of travellers is represented in a network equilibrium framework using the complementarity formulations of user equilibrium conditions for car mode by Ferris et al (1998) and partly for public transport mode by Cea and Fernandez (1993). The two models are used in combination in order to formulate the simultaneous user equilibrium for car and public transport modes with an elastic travel demand.

Route choices of network users are performed on the following two transport networks: car network and public transport network. Both networks consist of the same nodes, representing residential locations and locations of economic activities inside a city or a region, and different links between them. The collection of links between nodes of a given transport network is called the structure of network and it may be described using binary parameters. In general, there may be more than one link connecting a pair of nodes. In case of the car network, they are interpreted as alternative roads and are enumerated with the whole numbers. In case of the public transport network, they are interpreted as parts of different public lines and are enumerated according to the line they belong to. All links of the transport network are directed, which means that for a pair of nodes  $i$  and  $j$  there is a separate link leading from node  $i$  to node  $j$  and a separate link leading from node  $j$  to node  $i$ .

All transit lines  $r \in \{1, 2, \dots, L\}$  are divided into bus lines  $r \in R^b = \{1, \dots, L^b\}$  and other lines  $r' \in R^{nb} = \{L^b + 1, \dots, L\}$ . A public transport planner, who sets a unified price for the use of its services, operates all public transit lines except for bus lines. A certain fare  $\phi^p$  is charged for each trip on the transit lines operated by the planner. An equilibrium market fare  $\varphi_r$  is charged by oligopolistic bus operators for each trip on the bus line  $r$ . The level of this fare is the result of oligopolistic competition between identical operating firms and depends upon the size of the bus transit market (total demand for bus transit services) as well as the level of marginal and fixed/entry costs.

Denote by  $\delta_{ijn}$  a binary parameter representing the structure of car network, which equals unity if there exists a link number  $n$  leading from node  $i$  to node  $j$  and zero otherwise. In the same manner, denote by  $\gamma_{ij}^r$  a binary parameter representing the structure of public transport network, which equals unity if there exists a link of public line  $r$  leading from node  $i$  to node  $j$  and zero otherwise.

Each link of the transport network is associated with a generalized cost function representing both time costs in monetary value and monetary costs of travelling on the link. The generalized costs of travelling between each pair of nodes depend upon the route choices of citizens and are the sum of generalized link costs along the chosen route. The generalized travel costs for car  $c_{ij}^{car}$  and for public transport  $c_{ij}^{pub}$  define travel demands of the citizens according to the elastic

nested logit travel demand functions  $D_{ij}^{car}(c_{ij}^{car}, c_{ij}^{pub})$  and  $D_{ij}^{pub}(c_{ij}^{pub}, c_{ij}^{car})$ , where destination choice is at the highest nest and mode choice is at the lowest one.

Generalized cost functions of car network links are denoted by  $c_{ijn}(f_{ijn})$  and are increasing functions of total car flow on the link,  $f_{ijn}$ . These functions include time travel costs measured in monetary units, spending on petrol and other possible monetary costs, such as road charges for example. Generalized link cost functions also represent the phenomenon of congestion on city roads, which leads to increase in travel times on the links and hence increase in generalized link costs. The generalized travel costs for car  $c_{ij}^{car}$  are the sum of generalized link costs along the links of optimal route from node  $i$  to node  $j$ .

Generalized travel costs for public transport  $c_{ij}^{pub}$  consist not only of link transit costs  $t_{ijr}$  associated with each link of the public transport network, but also of waiting costs  $w_{ijr'r}(g_r)$  while changing line  $r'$  for line  $r$  at node  $i$ , that depend upon frequencies of the lines  $g_r$ . One should also account for public transit fares  $\phi^p$  and  $\phi_r$  that are charged for each trip on a transit line i.e. for each change of a transit line during a trip. The total generalized travel costs for public transport  $c_{ij}^{pub}$  consist of transit time and waiting costs measured in monetary units plus transit fares.

The user equilibrium formulation proposed in the paper allows one to formulate optimal route choice problems for both car and public transport modes

as the single mathematical problem in the following way (see Ivanova, 2004 for more details):

$$\sum_j \sum_n x_{ijn}^k \delta_{ijn} - \sum_j \sum_n x_{jin}^k \delta_{ijn} = D_{ik}^{car} (c_{ik}^{car}, c_{ik}^{pub}) \quad (5)$$

$$c_{ijn}(f_{ijn}) + c_{jk}^{car} - c_{ik}^{car} \geq 0 \perp x_{ijn}^k \geq 0 \quad (6)$$

$$f_{ijn} = \sum_k x_{ijn}^k + \sum_{r \in R^b} \gamma_{ij}^r g_r \quad (7)$$

$$\sum_j \sum_{r'} \sum_r y_{ijr'r}^k \lambda_{ijr'r} - \sum_j \sum_{r'} \sum_r y_{jir'r}^k \lambda_{ijr'r} = D_{ik}^{pub} (c_{ik}^{pub}, c_{ik}^{car}) \quad (8)$$

$$t_{ijr} + w_{ijr'r}(g_r) + \phi^p + c_{jk}^{pub} - c_{ik}^{pub} \geq 0 \perp y_{ijr'r}^k \geq 0 \text{ for } r \in R^{nb} \text{ and } r' \neq r \quad (9)$$

$$t_{ijr} + w_{ijr'r}(g_r) + c_{jk}^{pub} - c_{ik}^{pub} \geq 0 \perp y_{ijr'r}^k \geq 0 \text{ for } r \in R^{nb} \text{ and } r' = r \quad (10)$$

$$c_{ijn}(f_{ijn}) + w_{ijr'r}(g_r) + \varphi_r + c_{jk}^{pub} - c_{ik}^{pub} \geq 0 \perp y_{ijr'r}^k \geq 0 \text{ for } r \in R^b \text{ and } r' \neq r \quad (11)$$

$$c_{ijn}(f_{ijn}) + w_{ijr'r}(g_r) + c_{jk}^{pub} - c_{ik}^{pub} \geq 0 \perp y_{ijr'r}^k \geq 0 \text{ for } r \in R^b \text{ and } r' = r \quad (12)$$

$$f_{ijr}^p = \sum_k \sum_{r'} y_{ijr'r}^k \quad (13)$$

$$\Phi^r = \sum_i \sum_j \sum_{r'} \sum_k (y_{ijr'r}^k \lambda_{ijr'r} - y_{jir'r}^k \lambda_{jir'r}) \quad (14)$$

where  $x_{ijn}^k$  is a car flow on a link number  $n$  from node  $i$  to node  $j$  with destination at node  $k$ .  $y_{ijr'r}^k$  is a flow of passengers on a link from node  $i$  to node  $j$ , which belongs to the public line  $r$ , with destination at node  $k$ , who change line  $r'$  for line  $r$  at node  $i$ .  $\lambda_{ijr'r} \in \{0,1\}$  are derived in the following way  $\lambda_{ijr'r} = \max\{\max_k \{\gamma_{ki}^{r'}\}, \gamma_{ij}^{r'}\}$ . It equals unity, when there is a possibility to change

line  $r'$  for line  $r$  at node  $i$  and continue travelling on link from node  $i$  to node  $j$ .  $N_r^{veh}$  is the capacity of buses operating at line  $r$  used in order to transform bus passengers into vehicles.

The mathematical formulation of market equilibrium for bus transit services (1)-(14) belongs to the wide class of mathematical problems called Mixed Complementary Problems (MCP) and may be solved using standard algorithms for these types of problems implemented in a modelling package such as GAMS for example.

### **3. Numerical results and their welfare implications**

Empirical analysis performed in this section utilizes the MCP formulation of bus transit market equilibrium presented in Section 2. Consequences of the congestion road pricing are evaluated under different assumptions about the competitive structure of bus transit market including the present situation, when bus fares are set by a regional regulator, oligopoly, monopoly and perfect competition.

Formulation of the model (1)-(14) used for simulations utilizes a simplified structure of the regional network. In particular, the total number of bus lines is reduced to six and the number of other public transport lines is reduced to three (metro, tram and train). The aggregation scheme of the existing bus lines correspond to the present situation on the bus transit market, where all existing bus lines are operated by three large firms holding a tender from the regional regulator. Each of the aggregate lines is operating by one of these firms. Such

simplification implies that a firm operating an aggregated bus line in reality operates several existing bus lines, which increases the value of its demand as well as the number of vehicles necessary in order to operate this line.

The level of marginal costs per passenger for each of the three aggregate bus lines  $r \in \{1,2,3\}$  in NOK has been calculated according to the following formula:

$$MC_r = R_r \cdot 0.007 \cdot 9 + \frac{2R_r}{S_r} g_r (R_r \cdot 3.3 \cdot 9 + 463) \frac{\eta_r}{\Phi_r}$$

Where the first term represents the costs of petrol used per each additional passenger and the second term represents the costs of operating the chosen number of vehicles (including petrol costs and drivers wage) divided by the total number of passengers on the line.

The level of total costs for each of the lines in NOK per vehicle  $fc_r$  has been set equal to 572 NOK, which is equal to the total vehicle price (1.6 mil NOK) divided by the total number of working days in 10 years. It is supposed that the full vehicle price should be recovered during this period of time afterwards an old vehicle is replaced by a new one. Vehicle capacity  $N_r^{veh}$  is assumed to be equal 163 passengers. The calculated marginal costs of bus lines at the initial are represented at Table 1.



**Table 1: Marginal costs of the bus lines in NOK**

Number of a bus line	Marginal costs
1	13.8
2	10.3
3	6.8
4	2
5	4
6	8.9

The generalized cost functions of car network links  $c_{ijn}(f_{ijn})$  are supposed to have the following functional form

$$c_{ijn}(f_{ijn}) = \Omega L_{ijn} t_{ijn}^0 \left( 1 + \beta_{ijn} \left( \frac{f_{ijn}}{K_{ijn}} \right)^{\alpha_{ijn}} \right)$$

Where  $L_{ijn}$  is the length of link in km,  $\Omega$  is the monetary value of time,  $t_{ijn}^0$  is the free-flow travel time per km,  $\beta_{ijn}$  and  $\alpha_{ijn}$  are technical parameters of the function and  $K_{ijn}$  is the capacity of the link. Given this functional form of link cost functions, congestion charges at each link  $\xi_{ijn}$  are derived as follows

$$\xi_{ijn} = \frac{\partial c_{ijn}}{\partial f_{ijn}} = \Omega L_{ijn} t_{ijn}^0 \beta_{ijn} \alpha_{ijn} \left( \frac{f_{ijn}}{K_{ijn}} \right)^{\alpha_{ijn}-1} \frac{1}{K_{ijn}}$$

Given that congestion road pricing is implemented at each link of the car network the new generalized link costs are defined as the sum of  $c_{ijn}(f_{ijn})$  and  $\xi_{ijn}$ . By comparing results of the model (1)-(14) with the old generalized link costs and with the modified ones one may estimate the effects of congestion pricing using keeping the structure of bus transit market as given. Given that the present level of

public transit fare is about 5 NOK, the estimated increase in public transit demand resulting from congestion pricing is 1022 trips per day and the revenue from road pricing is 269 275 NOK per day.

The average speed of bus vehicle  $S_r$  in km/hour is supposed to be equal to the average vehicle speed on the car network and is calculated as follows

$$S_r = \frac{\sum_i \sum_j \sum_n L_{ijn} \left( t_{ijn}^0 \left( 1 + \beta_{ijn} \left( \frac{f_{ijn}}{K_{ijn}} \right)^{\alpha_{ijn}} \right) \right)^{-1}}{\sum_i \sum_j \sum_n L_{ijn}}$$

In case of private provision of bus transit services, implementation of the congestion pricing influences average speed of both car vehicles and buses and, hence, bus transit firms' choices of frequency and fare levels.

Table 2 presents the results of simulation with the model for the case of monopoly, duopoly, oligopoly with 5 and 10 firms and perfect competition with 100 firms in the form of change in bus travel demand  $\Delta D^{bus}$ , change in bus transit operators revenues  $\Delta Rev^{bus}$ , change in total profits of bus transit operators  $\Delta \pi^{total}$ , percentage change in average level of bus fare  $\Delta \varphi$ , the level of revenue from congestion pricing  $Rev^{cp}$ , total change in travellers' welfare  $\Delta W$  calculated as their consumer surplus/loss using functional forms nested logit travel demand functions  $D_{ij}^{car}$  and  $D_{ij}^{pub}$  and change in total welfare function defines as the sum of travellers' consumer surplus/loss, change in bus transit operators profits and

revenues from congestion road pricing  $\Delta W^{total}$ . All values presented at Table 2 are calculated per day.

**Table 2: Results of simulations with the model (1)-(14)**

	<b>Monopoly</b>	<b>Duopoly</b>	<b>Oligopoly (5 firms)</b>	<b>Oligopoly (10 firms)</b>	<b>Competition (100 firms)</b>
$\Delta D^{bus}$ (trips)	232	335	333	709	4 918
$\Delta Rev^{bus}$ (NOK)	4 962	-1 433	-629	612	22 093
$\Delta \pi^{total}$ (NOK)	6634	-141	-371	-235	21101
$\Delta \phi$	-0.18%	-0.67%	-0.58%	-0.35%	2.64%
$Rev^{cp}$ (NOK)	302 130	265 316	258 329	251 669	218 727
$\Delta W$ (NOK)	751	331	10	-298	472
$\Delta W^{total}$ (NOK)	309 515	265 506	257 968	251 136	240 300

Results of the performed model simulations demonstrate that demand for bus transit services increases as the result of congestion pricing and a value of its increase is positively related to the level of competition at the market. The direction of change in total revenues and total profits of bus transit operators induced by the demand increase varies with the competitive structure of the market. It is positive in case of monopoly and perfect competition and changes from negative to positive with the number of firms at the market in case of oligopoly. Such variation is explained by decrease in equilibrium oligopolistic bus fare, which neutralizes the positive effect of demand increase upon the revenues and profits. In case of perfect competition, congestion road pricing has positive effect on both demands and prices of bus transit operators resulting in revenue and profit increase. The value of congestion pricing revenue is closely related to the level of demand for car trips. Increase in public transit demand decreases the total

number of car trips and, hence, negatively influences congestion pricing revenue. In general, this revenue is decreasing with the level of competition at the bus transit market.

Results at Table 2 demonstrate that the travellers' total consumer surplus/loss depends upon the number of firms at the bus transit market in a complex non-linear manner. It is positive for the case of monopoly and decreases up to some negative value level with an increase in the number of firms at the market. As the competitive structure of the market becomes closer to perfect competition, travellers' total consumer surplus/loss increases and is positive in the case when 100 firms operate at the market. However, the value of travellers' surplus is higher in the case of monopoly than in the case of perfect competition. Observed pattern of the consumer surplus values is driven by interplay between changes in public transit demands and changes in bus transit fares.

The total welfare of congestion road pricing is positive and decreasing with the level of competition at the market, that is with the difference between equilibrium bus fare and marginal costs of the firms. This result is consistent with the findings of Parry and Bento (2000).

#### **4. Conclusions**

Discussions of congestion road pricing have paid relatively small attention to the potential effects of this policy upon the performance of public transit market as well as upon the relationship between welfare effects of congestion pricing and structure of the public transport market.

The present paper analysis the consequences of congestion road pricing in greater Oslo region of Norway upon its bus transit market under different assumptions about its competitive structure. Empirical analysis is performed using combined game theoretic and network equilibrium approach to modelling equilibrium on the bus transit market for the case of monopoly, duopoly, oligopoly and perfect competition.

Results of model simulations presented in the paper demonstrate that both travellers' consumer surplus/loss, profits of bus transit operators and congestion pricing revenues depend upon the structure of bus transit market. Introduction of the congestion pricing induce increase in the demand for bus trips and decrease in bus fares (for cases of monopoly, duopoly and oligopoly) resulting in the change in total bus operators' profits. The change in profits varies from positive in case of monopoly to negative in case of oligopoly and finally becomes positive under perfect competition. Travellers' consumer surplus/loss also changes from positive in case of monopoly to negative in some oligopoly cases to being positive under perfect competition. In general, congestion pricing revenue as well as the total congestion pricing welfare benefits decreases with the level of competition at the bus transit market.

The present paper has demonstrated that congestion pricing clearly influences performance of public transit sector along different directions and these effects should not be neglected while calculating the benefits of congestion road pricing or constructing its design. Moreover, both travellers' consumer benefit of congestion pricing and its revenues are influenced by the structure of public

transit market. Hence, present structure of this market and its possible future developments should be accounted for while analysis welfare effects of the congestion road pricing.

## References

Amir R. and Grilo I. (2003) On complementarity conditions in Bertrand oligopoly. *Economic Theory* 22, 227-232

Cea De J. and Fernandez E. (1993) Equilibrium model, *Transportation Science* 27(2), 133-147

Ferris, M. C. , Meeraus, A. and Rutherford, T. (1998) Computing Wardropian equilibria in a complementarity framework. *Optimization Methods and Software*, 10, 669-685.

Friedman J *Oligopoly and the theory of games*, North-Holland, Amsterdam

Gómez-Ibáñez J. A. and Small K. A. (1994) Road pricing for congestion management: A survey of international practice, *National Cooperative Highway Research Program, Synthesis of Highway Practice* 210, TRB, National Academy Press, Washington, DC

Harker P. T. (1984) A variational inequality approach for the determination of oligopolistic market equilibrium. *Mathematical Programming* 30, 105-111

Ivanova O. (2004) Formulation of simultaneous car and public transport network equilibrium in the form of mixed complementarity problem in the context of bi-level programming, accepted to *The Advances of Transportation Studies*

Knight F. (1924) Some fallacies in the interpretation of social costs. *Quarterly Journal of Economics* 38(4), 582-606

Nagurney A. (1993) *Network economics: a variational inequality approach*, Klurwer Academic Publishers

Parry I. W. H. and Bento A. (2000) Estimating the welfare effect of congestion taxes: The critical importance of other distortions within transport system, *Discussion Paper* 00-51, Resources for Future

Pigou A. C. (1920) *Wealth and welfare*. Macmillan, London.

Small K. A. (2003) Road pricing and public transport, to appear in *Road Pricing: Theory and Practice*, eds Santos G., Elsevier

Small K. A. and Gómez-Ibáñez J. A. (1998) Road pricing for congestion management: the transition from theory to policy, in *Road Pricing, Traffic Congestion and the Environment: Issues of Efficiency and Social Feasibility*, eds Button K. J. and Verhoef E. T., Edward Elgar: Cheltenham, UK

Vickrey W. S. (1963) Pricing in urban and suburban transport. *American Economic Review* 53, 452-465

Vives X. (1999) *Oligopoly pricing: old ideas and new tools*, Cambridge, MA: MIT Press

Williams H. C. W. L. and Abdulaal J. (1993) Public transport services under market arrangements, part I: A model of competition between independent operators, *Transportation Research B* 27(5), 369-387