Optimal Pricing of Urban Passenger Transport

A Simulation Exercise for Belgium

By Bruno De Borger, Inge Mayeres, Stef Proost and Sandra Wouters*

1. Introduction

Over the past decades increasing congestion and pollution levels in urban areas have widened the gap between the private and social costs of urban traffic. Economists typically suggest that an appropriate pricing policy, reflecting the relevant external costs of the various modes, should be an important part of any policy proposal. This raises several questions. The first problem is the computation of all relevant marginal social costs. This includes the valuation of time lost because of congestion, the valuation of reduced pollution and noise, and the valuation of changes in accident risks. Not surprisingly, these issues have been dealt with by several authors (see, for example, Newbery, 1988, 1990; and Jones-Lee, 1990). A second question is how to determine the optimal prices for car use and public transport. Under ideal conditions the economic prescription is to make transport users pay the marginal social costs of their consumption. However, in practice the problem may be more complicated if distributional considerations have to be taken into account, or if pricing restrictions impose additional constraints on the optimal pricing problem (see, for example, Bös, 1986; Glaister and Lewis, 1978). Price differentiation between peak and off-peak traffic may not be technically or politically feasible, or budget constraints may apply to the public transport authority. Finally, a third question relates to the numerical calculation of optimal prices. As the level of the marginal social cost of congestion and other externalities is itself a function of the intensity of car and bus use, an equilibrium optimum tax or price has to be computed which takes into account all demand and supply responses.

The aim of this paper is twofold. First, we analyse the introduction of social cost considerations in a theoretical pricing model of urban transport services. Although optimal prices under congested conditions were studied by economic theorists as early as

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the 1960s, other forms of external costs have not been considered equally carefully in theoretical models.¹ Our model explicitly incorporates congestion, pollution, noise, and accident risks. Second, we illustrate the use of a stylised version of the model to study optimal prices on the basis of available data for Belgian urban areas.

The developed model builds upon the seminal papers by Glaister and Lewis (1978), Small (1983) and Viton (1980, 1983). The Glaister and Lewis paper developed an urban passenger transport model which includes three transport modes, that is, the private car, bus and rail services. For each of these modes they consider two periods, peak and off-peak. Demand for each mode and each period is a function of the prices of all modes in the two periods. A congestion cost is associated with car use in the peak period. The model is used to derive optimal bus and rail prices under the assumption that car prices cannot be varied. In some sense, Small (1983) studied the reverse problem. He designed an optimal toll on an urban highway which is also used by an express bus service. In his model the bus price is fixed and only the toll can be varied. Individual demand data are used so that the welfare distribution effects of different toll regimes can be studied. Finally, Viton (1983) analysed a model of a two-mode urban transport system. Both private car and bus transport cause external environmental and congestion costs. The model determines optimal car and bus prices and optimal supply levels, ignoring distributional considerations.

In this paper we use an extended version of the Glaister and Lewis (1978) model, incorporating ideas of Viton (1983) and Small (1983). There are five extensions to the original model. First, at the theoretical level the welfare distribution dimension is explicitly introduced. Second, the social costs of both private and public transport modes are considered and include, besides congestion costs, environmental and accident costs. Third, the prices of both private and public transport are treated as policy variables. Fourth, the demand for the various transport services explicitly depends not only on prices but also on speed, as an indicator for the level of congestion. Finally, several types of pricing constraints such as the absence of discrimination possibilities between peak and off-peak periods, and the imposition of a budget constraint on the public transport sector are examined.

The structure of the paper is as follows. In Section 2 the theoretical model is presented. First, optimal prices if there are no restrictions on the pricing instruments are derived. However, in view of the application that follows we also consider optimal pricing for various special cases such as the imposition of budgetary restrictions, or the impossibility, for social or political reasons, to discriminate between peak and off-peak prices. The application of a simplified version of the model to urban transport in Belgium is presented in Section 3. The specification of the demand and supply sides of the model is discussed, the data used for Belgium are reviewed, and information on the calculation of the external costs is provided. Here extensive use is made of Mayeres (1993), in which all relevant marginal external costs of car use in Belgium are computed. Section 4 contains a careful discussion of the empirical results. Finally, the conclusions are summarised in Section 5.

2. The Theoretical Model

In this section a static partial equilibrium model of the urban passenger transport market is developed. It must be emphasised at the outset that all pricing models in this tradition have several important limitations. They implicitly assume a given location of individuals and given infrastructure. Moreover, this type of model is in general not spatially disaggregated. The network infrastructure is represented by one link, which is subject to congestion. Finally, it is assumed that there is no interference with freight transport.

Organisation of this section is as follows. In subsection 2.1 the structure of the model is presented. Optimal pricing rules are discussed in subsection 2.2. Optimal pricing rules in the absence of any policy restrictions are analysed first. The implications of constraints on the pricing instruments and formal budgetary restrictions on the transport sector are then consecutively considered.

2.1 The structure of the model

The model incorporates two transport modes: private car and public transport. For each mode a distinction is made between peak and off-peak traffic. The superscript notation used is: private car — peak\(^1\); private car — off-peak\(^2\); public transport — peak\(^3\); and public transport — off-peak\(^4\).

There are \( H \) households. In its extensive form, the utility of household \( h \) is written as a function of the quantity consumed of a composite numeraire good \( x_h \), of its use of the four types of transport services \( x^i_h \) (the number of kilometres individual \( h \) travels by transport service \( i \) \((i = 1, \ldots, 4)\)), and of a set of other variables that allow us to identify the major external effects associated with transport services in peak and off-peak periods. Specifically,

\[
U_h = U_h (x_h, x^1_h, \ldots, x^4_h, y^1, \ldots, y^4, E, CA^1, \ldots, CA^4) \text{ for all } h
\]

where \( y^i \) is the average speed of transport service \( i \), \( E \) serves as an indicator of the level of environmental pollution and \( CA^i \) represents the number of accidents associated with transport service \( i \).

It is assumed that \( y^i, E \) and \( CA^i \) are taken as exogenously given by each household. Note, however, that these externality-related variables indirectly depend on traffic levels. To be specific, average speed during peak and off-peak periods is given by:

\[
y^i = y^i(Q^1, Q^3) \text{ for } i = 1, 3
\]

\[
y^i = y^i(Q^2, Q^4) \text{ for } i = 2, 4
\]

where \( Q^i \) gives the total number of vehicle-km travelled by transport service \( i \), and all partial derivatives are negative, reflecting that average speed decreases with \( Q^i \). With respect to the relation between vehicle-km and passenger-km we simply assume fixed occupancy rates for passenger cars and public transport vehicles:

\[
Q^i = Q^i(X^i) \text{ for all } i
\]

where \( X^i \) is the total number of passenger-km travelled by transport service \( i \). In other words, we do not explicitly model the optimal provision of services by the public transport authority, but assume in this paper that the public transport firm adjusts its supply of vehicle-km in response to demand. Although this passive behaviour of the public transport
sector ignores a potentially important policy variable, it seems to be quite reasonable in the Belgian context, where average occupancy rates have remained quite stable over time. Note that this treatment of public transport supply behaviour has important implications for the determination of the marginal costs of additional passenger-km, to which we return later.

The level of environmental pollution \( E \) is defined as

\[
E = a + \sum_{i=1}^{k} CE^i(Q^i)
\]

where \( CE^i \) gives total environmental pollution by transport service \( i \), assumed to be positively related to \( Q^i \). Finally, the number of accidents associated with transport service \( i \) during peak and off-peak periods is given by

\[
CA^i = CA^i(Q^1,Q^2) \quad \text{for } i = 1, 3
\]

\[
CA^i = CA^i(Q^2,Q^4) \quad \text{for } i = 2, 4
\]

where the number of accidents is assumed to increase with traffic volume.

Using all the above structural relations, we can rewrite the individual’s utility function in reduced form:\(^2\)

\[
u_h = u_h(x_h, x^1_h, ..., x^d_h, X^1_h, ..., X^d_h) \quad \text{for all } h
\]

where all the \( X^i \) are taken as exogenous parameters by the individual. Assuming sufficient differentiability, we can define demand functions and an indirect utility function \( v \):

\[
v_h = v_h(P, p^1, ..., p^d, Y_h, X^1, ..., X^d) \quad \text{for all } h
\]

with corresponding extensive form \( V \):

\[
V_h = V_h(P, p^1, ..., p^d, Y_h, X^1, ..., X^d, E, CA^1, ..., CA^d) \quad \text{for all } h
\]

where \( P \) gives the price of the composite commodity, \( p^i \) is the out-of-pocket price of transport service \( i \), and \( Y_h \) represents the full income of individual \( h \). The individual’s compensated demand function for transport service \( i \) can be written as:

\[
x^i_h = x^i_h(P, p^1, ..., p^d, X^1, ..., X^d, u_h) \quad \text{for all } i, h
\]

Solving equation (9) for \( Y_h \) we find the individual expenditure functions \( g \):

\[
g_h = g_h(P, p^1, ..., p^d, X^1, ..., X^d, u_h) \quad \text{for all } h
\]

Using the duality results for public goods (see King, 1986), we can define the marginal external cost (\( mec^i_h \)) of an increase in the traffic level \( i \) for individual \( h \) as

\[
mec^i_h = \frac{\partial g_h(P, p^1, ..., p^d, X^1, ..., X^d, u_h)}{\partial X^i} = - \frac{\partial v_p / \partial X^i}{\partial v / \partial Y^i}
\]

These marginal external costs include external congestion, environmental and accident costs induced by additional traffic of type \( i \).\(^3\)

Finally, we assume the variable production costs of private and public transport services to be given by

\[
C^i = C^i(Q^i, X^i) \quad \text{for all } i
\]

\(^2\) To avoid confusion we use \( U \) for the extensive form and \( u \) for the reduced form of the utility function. A similar notation will be used to distinguish the extensive form (\( V \)) from the reduced form (\( v \)) in the case of the indirect utility function.

\(^3\) For the full theoretical specification of the marginal external costs, see De Borger et al. (1994).
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which can be rewritten in reduced form using equation (4)
\[ c^i = c^i(X^i) \text{ for all } i \]  \hspace{1cm} (15)

The public transport authority is assumed to operate a given public transport network. Total costs of public transport are given by the sum of total variable costs and fixed costs, \( FC \).

2.2 Optimal pricing rules

2.2.1 No restrictions on pricing

Optimal pricing decisions derived in a partial equilibrium model of the transport sector are only "globally" optimal if there are no distortions in the other sectors of the economy. These distortions clearly exist and are difficult to take into account in a partial equilibrium model. One of the most important distortions is the impossibility of lump sum taxation and redistribution for the government.\(^4\) In a partial equilibrium framework this can be translated to a starting situation where the vector of after-tax incomes does not guarantee the equality of the social marginal utilities of income and where there is a marginal cost of public funds \((1 + \lambda)\) larger than one (Laffont and Tirole, 1990).

The choice of optimal transport prices and taxes can then be formulated as
\[ \max_{p^1, p^2, p^3, p^4} W(v_1, \ldots, v_h, \ldots, v_4) \]
\[ + (1 + \lambda) \left[ \sum_{i=1}^{4} (p^i X^i - c^i) - FC \right] \]
\[ X^i \geq 0, \, p^i \geq 0 \]  \hspace{1cm} (16)

in which \( W \) is a social welfare function of the Bergson-Samuelson type.

Differentiating with respect to \( p^j \) and using Roy’s identity and the duality results of King (1986), yields the following first-order necessary conditions for a maximum\(^5\)
\[ \sum_h \sigma_h \left( -x^i_h - \sum_{j=1}^{4} \frac{\partial X^i_j}{\partial X^i} X^i_j \right) + (1 + \lambda) \left[ - \sum_{j=1}^{4} \frac{\partial c^i}{\partial X^i} X^i_j + \sum_{j=1}^{4} p^j X^i_j + X^i \right] = 0 \]
\[ j = 1, \ldots, 4 \]  \hspace{1cm} (17)

where \( X^i_j \) represents the effect of an increase in the price of transport service \( j \) on the aggregate demand for traffic of type \( i \), and \( \sigma_h \) represents the marginal social utility of income:\(^6\)
\[ \sigma_h = \frac{\partial W}{\partial v_h} \left( \frac{\partial v_h}{\partial Y_h} \right) \]

\(^4\) The optimal tax problem in the presence of externalities has been dealt with in a general equilibrium framework by Bovenberg and Van der Ploeg, 1994. For a first general equilibrium application to the taxation of car use see Mayeres and Proost, 1994.

\(^5\) In this model the presence of fixed costs and externalities implies non-convexities. It is well known that in this case the first-order conditions may be insufficient and that, moreover, corner solutions could be optimal. We restrict ourselves to a discussion of non-corner solutions (Guesnerie, 1980; and Bős, 1985).

\(^6\) For one reference individual \((h = 1)\) the welfare weight is set equal to one. This convention is necessary in order to have a fully defined marginal cost of public funds \((1 + \lambda)\).
It is useful to define the marginal social costs \( S^i \) associated with an additional unit of \( X^i \) as:

\[
S^i = \sum_{h} \sigma_h m e c_i^h + \frac{\partial c_i^h}{\partial X^i} \quad \text{for all } i
\]  \( (19) \)

This expression indicates that the social marginal cost of an extra unit of traffic of type \( i \) equals the weighted sum of the marginal external costs as defined in (13) and the marginal resource costs.

Using the definition of marginal social costs in (19), the optimal pricing rules (17) can be rewritten as:

\[
\begin{bmatrix}
\eta_1 & \eta_2 & \eta_3 & \eta_4 \\
\eta_5 & \eta_6 & \eta_7 & \eta_8 \\
\eta_9 & \eta_{10} & \eta_{11} & \eta_{12}
\end{bmatrix}
\begin{bmatrix}
[S^1 + \lambda \frac{\partial c_1}{\partial X^1} - (1 + \lambda)p^1]X^1 \\
[S^2 + \lambda \frac{\partial c_2}{\partial X^2} - (1 + \lambda)p^2]X^2 \\
[S^3 + \lambda \frac{\partial c_3}{\partial X^3} - (1 + \lambda)p^3]X^3 \\
[S^4 + \lambda \frac{\partial c_4}{\partial X^4} - (1 + \lambda)p^4]X^4
\end{bmatrix}
= -
\begin{bmatrix}
\sum_{h} \sigma_h \frac{x_h^1}{X^1} - (1 + \lambda) \\
\sum_{h} \sigma_h \frac{x_h^2}{X^2} - (1 + \lambda) \\
\sum_{h} \sigma_h \frac{x_h^3}{X^3} - (1 + \lambda) \\
\sum_{h} \sigma_h \frac{x_h^4}{X^4} - (1 + \lambda)
\end{bmatrix}
\begin{bmatrix}
X^1 p^1 \\
X^2 p^2 \\
X^3 p^3 \\
X^4 p^4
\end{bmatrix}
\]  \( (20) \)

Although the interpretation of these rules is quite complicated in general, interpretation becomes straightforward and intuitive if one assumes that the government can use first-best instruments (so that \( \lambda = 0 \)) and all welfare weights are equal to 1.\(^7\) As data limitations forced us to ignore distributional issues in the application described in the next section, it is useful to consider the pricing rules under these simplifying assumptions. It is easily seen that in that case social marginal cost pricing is a solution to the optimality conditions:

\[
p^i = S^i \quad \text{for all } i
\]  \( (21) \)

2.2.2 Pricing restrictions with no difference between peak and off-peak prices

Hitherto we have considered the case in which there are no restrictions on pricing. In reality, however, it is often infeasible, for practical or political reasons, to charge a different price for peak and off-peak travel. Therefore the case where price differentiation between peak and off-peak travel is impossible for all modes needs to be considered. In that case, peak prices must equal off-peak prices both for private and public transport. We introduce \( p^p \) and \( p^o \) as the price charged to private car and public transport users, respectively. Expression (16) can then be reformulated using only these two prices as policy variables. Using Roy’s identity, the duality results of King and equation (19), the first-order necessary conditions for a maximum can then be written as:

\(^7\) For a discussion of the optimal pricing formulae in a situation where first-best instruments are not available, see De Borger et al. (1994).
where $\eta_i^c(\eta_i^p)$ is the car (bus) price elasticity of transport service $i$.

As previously noted, in the simulation exercise reported below we assume that firstbest redistributive taxation instruments are available. First-order conditions are then given by

$$\begin{bmatrix}
\eta_1^c & \eta_2^c & \eta_3^c & \eta_4^c \\
\eta_1^p & \eta_2^p & \eta_3^p & \eta_4^p
\end{bmatrix}
\begin{bmatrix}
(S^1 - p^c)X^1 \\
(S^2 - p^c)X^2 \\
(S^3 - p^c)X^3 \\
(S^4 - p^c)X^4
\end{bmatrix} = 
\begin{bmatrix}
0 \\
0
\end{bmatrix}
$$

(23)

To facilitate the interpretation of these expressions, it is useful to assume that all cross-price elasticities of demand ($\eta_1^p, \eta_2^p, \eta_3^c, \eta_4^c$) are zero. In that case it is easily shown that prices are a weighted average of marginal social costs in the peak and the off-peak periods, where the period that is most price-responsive is given the highest weight.

2.2.3 Budget constraint for the public transport sector

Finally the implications for optimal transport fares of the imposition of a formal budget constraint on the public transport sector are analysed. We consider maximisation problem (16) subject to

$$FC + \sum_{i=3}^{n} p^i \eta_i^c = \sum_{i=3}^{n} p^i \eta_i^p X^i$$

(24)

The resulting first-order conditions describing optimal pricing can conveniently be rewritten as:

$$\begin{bmatrix}
\eta_1^c & \eta_2^c & \eta_3^c & \eta_4^c \\
\eta_1^p & \eta_2^p & \eta_3^p & \eta_4^p
\end{bmatrix}
\begin{bmatrix}
(S^1 + \lambda \frac{\partial c_1}{\partial X^1} - (1 + \lambda)p^1)X^1 \\
(S^2 + \lambda \frac{\partial c_2}{\partial X^2} - (1 + \lambda)p^2)X^2 \\
(S^3 + (\lambda - \mu) \frac{\partial c_3}{\partial X^3} - (1 + \lambda - \mu)p^3)X^3 \\
(S^4 + (\lambda - \mu) \frac{\partial c_4}{\partial X^4} - (1 + \lambda - \mu)p^4)X^4
\end{bmatrix} = 
\begin{bmatrix}
\sum_{h} \sigma_h \frac{x_h^1}{X^1} -(1 + \lambda)X^1 p^1 \\
\sum_{h} \sigma_h \frac{x_h^2}{X^2} -(1 + \lambda)X^2 p^2 \\
\sum_{h} \sigma_h \frac{x_h^3}{X^3} -(1 + \lambda - \mu)X^3 p^3 \\
\sum_{h} \sigma_h \frac{x_h^4}{X^4} -(1 + \lambda - \mu)X^4 p^4
\end{bmatrix}
$$

(25)
where $\mu$ is the multiplier associated with the budget constraint.

With respect to the simulation exercise that follows it is instructive to consider the pricing rules on the assumption that the government can use first-best redistributive taxation instruments. They are given by

\[
\begin{bmatrix}
\eta_1 & \eta_2 & \eta_3 & \eta_4 \\
\eta_2 & \eta_3 & \frac{\partial c_2}{\partial X_2} & \frac{\partial c_3}{\partial X_2} \\
\eta_3 & \frac{\partial c_3}{\partial X_3} & \frac{\partial c_3}{\partial X_3} & \frac{\partial c_3}{\partial X_3} \\
\eta_4 & \frac{\partial c_4}{\partial X_4} & \frac{\partial c_4}{\partial X_4} & \frac{\partial c_4}{\partial X_4}
\end{bmatrix}
\begin{bmatrix}
(S^1 - p^1)X^1 \\
(S^2 - p^2)X^2 \\
(S^3 - \mu \frac{\partial c_3}{\partial X_3} - (1 - \mu)p^3)X^3 \\
(S^4 - \mu \frac{\partial c_4}{\partial X_4} - (1 - \mu)p^4)X^4
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
-\mu X^3 p^3 \\
-\mu X^4 p^4
\end{bmatrix}
\]  

(26)

If one assumes zero cross-price elasticities of demand then it is easy to see that one obtains marginal social cost pricing for the private transport mode. Optimal public transport fares, on the other hand, are adjusted in order to satisfy the budget constraint.

3. Implementing the Model

Different routes can be taken to apply the optimal pricing model presented in the previous section. As is common in the empirical literature, our choice was dictated by the available empirical information. Following Glaister and Lewis (1978) we used aggregate data, and we were, unfortunately, forced to ignore distributional considerations.

3.1 Specification of the demand functions

The model has to be interpreted as reflecting an “aggregate” Belgian urban area, consisting of all Belgian cities offering public urban transport. These include Antwerp, Brussels, Ghent, Charleroi, Liège and Verviers. Implementation of the model is based on two transport modes, the private car and an aggregate public transport mode, consisting of both bus and tram.\(^8\) For the two modes considered, a distinction is made between peak and off-peak periods. Based on information in STRATEC (1992) and NIS (1985), the peak period is assumed to cover five hours a day, from 0700 to 0900, and from 1600 to 1900. The off-peak period covers seventeen hours: 0400 to 0700, 0900 to 1600 and 1900 to 0200. Traffic between 0200 and 0400 is negligible.

In the simulation exercises reported below, the aggregate demand functions for the different transport services ($X^i$) were taken to be simple loglinear functions of all relevant prices ($p^j$) and of average speed ($y^j$):

\[
X^i = \alpha^i \exp \left( \sum_{j=1}^{4} \eta^i_j \ln(p^j) + \tau^i_j \ln(y^j) \right)
\]  

(27)

\(^8\) Metro transport, which is offered only in Brussels, has been left out of the analysis. For more details, see De Borger et al. (1994).
### Table 1
**Price Elasticities**

<table>
<thead>
<tr>
<th>Price</th>
<th>Demand</th>
<th>Peak Car</th>
<th>Off-peak Car</th>
<th>Peak Bus/Tram</th>
<th>Off-peak Bus/Tram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Car</td>
<td>-0.3</td>
<td>0.049</td>
<td>0.708</td>
<td>0</td>
<td>0.578</td>
</tr>
<tr>
<td>Off-peak Car</td>
<td>0.05</td>
<td>-0.6</td>
<td>0</td>
<td>-0.35</td>
<td>0.036</td>
</tr>
<tr>
<td>Peak Bus/Tram</td>
<td>0.03</td>
<td>0</td>
<td>-0.35</td>
<td>0.03</td>
<td>-0.87</td>
</tr>
<tr>
<td>Off-peak Bus/Tram</td>
<td>0</td>
<td>0.02</td>
<td>0</td>
<td>-0.87</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2
**Daily Demand and Prices (1989)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x^1$</td>
<td>47,312,533</td>
<td>passenger-km</td>
<td>demand for peak car</td>
</tr>
<tr>
<td>$x^2$</td>
<td>48,695,041</td>
<td>passenger-km</td>
<td>demand for off-peak car</td>
</tr>
<tr>
<td>$x^3$</td>
<td>1,544,494</td>
<td>passenger-km</td>
<td>demand for peak bus and tram</td>
</tr>
<tr>
<td>$x^4$</td>
<td>1,297,262</td>
<td>passenger-km</td>
<td>demand for off-peak bus and tram</td>
</tr>
<tr>
<td>$p^1$</td>
<td>2.665</td>
<td>BF per passenger-km</td>
<td>price for peak car</td>
</tr>
<tr>
<td>$p^2$</td>
<td>2.665</td>
<td>BF per passenger-km</td>
<td>price for off-peak car</td>
</tr>
<tr>
<td>$p^3$</td>
<td>3.46</td>
<td>BF per passenger-km</td>
<td>price for peak bus and tram</td>
</tr>
<tr>
<td>$p^4$</td>
<td>3.46</td>
<td>BF per passenger-km</td>
<td>price for off-peak bus and tram</td>
</tr>
</tbody>
</table>

where $\eta_j^i$ are the price elasticities, assumed to be constant, and the $\tau_i^j$ are the elasticities of demand with respect to speed.\(^9\) To calibrate these demand functions information was needed on all relevant elasticities and on prices, quantities and speed in the base period. The relevant data were taken from the empirical literature (for example, Oum, Waters and Yong, 1992) and from a variety of transport studies using Belgian data (Boniver, 1992; Cuijpers, 1992; De Borger and De Borger, 1987; and STRATEC, 1992). Demand elasticities with respect to speed were taken from Van de Voorde (1981), Webster (1977) and Ruitenber (1983). Relevant values used amounted to 0.8 for public transport and 0.2 for private car use. We were unfortunately unable to find time elasticities that differentiated between the peak and off-peak periods. Vehicle occupancy rates were assumed to be 1.7 for private car and 50 and 30 for peak and off-peak public transport, respectively. Other relevant information used in the simulations is summarised in Tables 1 and 2. All information given refers to the year 1989.\(^10\)

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\(^9\) Note that demand for service $i$ only depends on the average speed of service $i$, because it is assumed that the ratio of average speed in private and public transport is constant (see below).

\(^10\) Note that in 1989 $\$1$ (US) corresponded to 39.43BF (Belgian Francs) and £1 sterling was equal to 64.55BF.
3.2 Marginal social costs of the different modes

The marginal social costs caused by an additional vehicle-km consist of external costs (congestion costs, air pollution costs, noise costs and accident costs) and private money costs. We first review the calculation of the various external costs, and then turn to private money costs.

3.2.1 Marginal congestion costs

The procedure for calculating marginal congestion costs as a function of traffic levels consisted of two steps. Marginal congestion, that is, the time loss suffered by road users due to an extra vehicle-km, was calculated first. The resulting relation was then combined with information on traffic composition and the respective values of time of car and public transport users to yield an estimate of marginal congestion costs.

To calculate marginal congestion, we introduced a relation describing how average speed is influenced by the number of passenger car equivalent unit (PCU) kilometres.\(^{11}\) This “capacity-speed” relation was based on several relatively crude “observations” on average speed and traffic levels.\(^{12}\) Denoting the number of vehicle equivalent kilometres per hour travelled in the aggregate city by \(PCU_{km/h}\) and average speed by \(v\), the following parabolic relation was derived:

\[
PCU_{km/h} = 6,133,949 + 138,926.12 \cdot y - 5,232,102 \cdot y^2
\]

(28)

where \(PCU_{km/h} = (PC_km + 2*PTV_km)/5\) for the peak and \(PCU_{km/h} = (PC_km + 2*PTV_km)/17\) for the off-peak period. In these expressions \(PC_km\) stands for the number of passenger car-km and \(PTV_km\) is the number of public transport vehicle-km. (Note that account has been taken of the respective lengths of peak and off-peak periods; 5 and 17 hours, respectively.) Inverting this relation, selecting the positive root, and taking the derivative with respect to \(PCU_{km/h}\) allows us to calculate the marginal effect of an extra PCU-km on the average time needed to drive one kilometre.

Let this change in travel time for one individual traveller caused by an additional PCU-km to be denoted by \(L^i\). Using the information that in the current situation average speed of public transport vehicles amounted to approximately 77 per cent of average car speed, the monetary value of the total marginal time loss of an additional vehicle-km driven in the peak period was expressed as

\[
L^i \cdot X^1 \cdot 230 + L^i/0.77 \cdot X^3 \cdot 124, i = 1,3
\]

(29)

where 230BF per hour and 124BF per hour are the respective values of in-vehicle time for car and public transport users,\(^{13}\) and, as before, \(X^1\) and \(X^3\) are the number of passenger-km travelled by car and by public transport, respectively.

\(^{11}\) 1 passenger car (PC) = 1 passenger car equivalent unit (PCU), and 1 public transport vehicle (PTV) = 2 passenger car equivalent units (PCU).

\(^{12}\) Specifically, the assumption that travel speed of freely flowing traffic is 50 km/h, was combined with two recent crude observations, that average speed in the current peak period (5,592,841 PCU-km per hour) is approximately 30 km/h, and that average speed drops to 10 km/h with a traffic level of approximately 7,000,000 PCU-km per hour.

\(^{13}\) These figures for the values of time were derived from the extensive survey results by Hague Consulting Group (1990). Converting the reported figures into 1989 Belgian Francs yielded 230BF and 124BF, respectively.
3.2.2 Marginal external air pollution, noise and accident costs

Because the data available are limited, all marginal external costs other than congestion costs are assumed to be independent of traffic levels. Three categories of marginal external costs are considered: air pollution costs, noise costs and accident costs. The determination of the marginal external costs other than congestion is carefully described in Mayeres (1993). A summary of the procedures used is reported in the Appendix to this paper.

Marginal external air pollution costs associated with the use of a private car are estimated to be 0.6018BF per km. The corresponding figure for public transport is 2.346BF per vehicle-km. The marginal external noise costs associated with an additional public transport vehicle-km are 3.45BF and 9.34BF for the peak and the off-peak periods respectively. For car transport, marginal external noise costs are found to be negligible (Mayeres, 1993). The marginal accident costs for car use amount to 1.6145BF per km. The additional accident costs caused by an additional public transport vehicle-km are calculated to be 7.5286BF.

3.2.3 Marginal private money costs

We now turn to an evaluation of marginal private money costs. For car use these include expenses on fuel, tyres, oil and maintenance associated with an extra vehicle-km. The average variable private money costs, exclusive of taxes,\(^\text{14}\) were used as an approximation of the relevant marginal costs. The average variable private money costs for car use were based on Cuijpers (1992), Zierock et al. (1989) and NIS (1990).\(^\text{15}\) They were estimated at 2.82005BF per km. Note that these costs were assumed not to depend on traffic levels. In other words, the non-zero but empirically small effect of traffic levels on energy consumption was ignored.

For public transport, the marginal private cost of an additional vehicle-km for the off-peak period was similarly approximated by the average variable cost, consisting of expenditures on drivers, on energy (insofar as this could be related to rolling stock operations), on materials and on maintenance. Relevant information was taken from the careful study by Evrard (1992). It was found that average variable private money costs amounted to 37.7BF per km. The corresponding value for the peak period was found to be 48.7BF per vehicle-km. In order to approximate long-run marginal costs, even if crudely, we allocated the marginal cost of rolling stock completely to the peak period.\(^\text{16}\) In other words, this marginal cost was added to the 48.7BF for the peak period.\(^\text{17}\)

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\(^{14}\) The price consumers have to pay for fuel, tyres, oil, repairs and insurance can be interpreted as the producer price plus taxes. The difference between the optimal price (to be determined) and the corresponding producer price equals the optimal tax to be levied on that good.

\(^{15}\) The variable private money costs are weighted by the proportion of total vehicle-km travelled with petrol, diesel and LPG cars.

\(^{16}\) For the calculation of the marginal cost of rolling stock we refer to De Borger et al. (1994) Appendix 5.

\(^{17}\) The model assumes that rolling stock is adjusted according to variations in demand. An increase in public transport passengers means more buses, and extra buses imply additional capacity, congestion, accident and environmental costs. The model allocates these marginal costs to the passengers using public transport, such that the marginal cost associated with an additional public transport user is approximated by the average cost. However, it can be argued that the only marginal costs caused by an additional passenger are the marginal boarding and alighting time costs (Mohring, 1972; and Turvey and Mohring, 1975).
Table 3
Marginal Social Costs of an Additional Passenger-km in 1989 for the Different Transport Modes
Monetary Valuations (BF per Passenger-km)

<table>
<thead>
<tr>
<th></th>
<th>Passenger Car</th>
<th></th>
<th>Bus and Tram</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak</td>
<td>Off-peak</td>
<td>Peak</td>
<td>Off-peak</td>
</tr>
<tr>
<td>Marginal external congestion costs</td>
<td>8.2292</td>
<td>0.5739</td>
<td>0.559</td>
<td>0.0639</td>
</tr>
<tr>
<td>Marginal external air pollution costs</td>
<td>0.354</td>
<td>0.354</td>
<td>0.0469</td>
<td>0.0782</td>
</tr>
<tr>
<td>Marginal external noise costs</td>
<td>negligible</td>
<td>negligible</td>
<td>0.069</td>
<td>0.3113</td>
</tr>
<tr>
<td>Marginal external accident costs</td>
<td>0.9497</td>
<td>0.9497</td>
<td>0.1506</td>
<td>0.2509</td>
</tr>
<tr>
<td>Average variable private money costs</td>
<td>1.65885</td>
<td>1.65885</td>
<td>3.704</td>
<td>1.257</td>
</tr>
</tbody>
</table>

3.2.4 Marginal social costs: summary of input data in the simulations
To give an idea of the order of magnitude for the various marginal social costs an overview is presented in Table 3. The table shows numerical values per passenger-km using the observed traffic flows for 1989 and relevant estimates for vehicle occupancy rates of 1.7, 50 and 30 for the private car, peak public transport and off-peak public transport, respectively. Interestingly, the results suggest that during the peak period marginal social costs resulting from congestion by far exceed those resulting from pollution, noise and accident risks. Of course, one should be careful with these comparisons, because in our model marginal congestion costs positively depend on traffic levels.

4. Some Simulation Results for Belgium
In this section, we report a number of simulation results obtained using the models outlined earlier. The structure of this section is as follows. First, the basic model in which no budgetary nor other restrictions are imposed is discussed in detail. We look at optimal prices and corresponding traffic levels, consider marginal social costs and average speeds at the optimum, and compare the optimal values with the observed values of the current situation. Second, we analyse optimal prices in the case where, because of political or technical reasons, the government does not have the possibility of discriminating between peak and off-peak periods of the day. Third, we analyse the implications of imposing a budget constraint on the public transport sector. Finally, in order to be able to compare our

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18 The simulation results were obtained using the non-linear optimisation program GAMS/MINOS (Brooke et al., 1992).
Optimal Pricing of Urban Passenger Transport

Table 4
Optimal Pricing Results
(no budgetary nor other restrictions)

<table>
<thead>
<tr>
<th></th>
<th>Initial Situation</th>
<th>Basic Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal Values</td>
<td>Percentage Change with respect to Initial Situation</td>
</tr>
<tr>
<td>Prices (BF per passenger-km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>2.67</td>
<td>6.67</td>
</tr>
<tr>
<td>Peak</td>
<td>2.67</td>
<td>6.67</td>
</tr>
<tr>
<td>Off-peak</td>
<td>2.67</td>
<td>6.67</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>3.46</td>
<td>4.22</td>
</tr>
<tr>
<td>Peak</td>
<td>3.46</td>
<td>1.95</td>
</tr>
<tr>
<td>Off-peak</td>
<td>3.46</td>
<td>-43.55</td>
</tr>
<tr>
<td>Marginal Social Costs (BF per passenger-km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>11.19</td>
<td>6.67</td>
</tr>
<tr>
<td>Peak</td>
<td>11.19</td>
<td>6.67</td>
</tr>
<tr>
<td>Off-peak</td>
<td>11.19</td>
<td>6.67</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>3.54</td>
<td>3.46</td>
</tr>
<tr>
<td>Peak</td>
<td>4.53</td>
<td>4.22</td>
</tr>
<tr>
<td>Off-peak</td>
<td>1.96</td>
<td>1.95</td>
</tr>
<tr>
<td>Traffic Flow (mio passenger-km per day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>47.31</td>
<td>37.85</td>
</tr>
<tr>
<td>Peak</td>
<td>47.31</td>
<td>37.85</td>
</tr>
<tr>
<td>Off-peak</td>
<td>47.31</td>
<td>37.85</td>
</tr>
<tr>
<td>Total</td>
<td>96.01</td>
<td>81.00</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>1.54</td>
<td>3.09</td>
</tr>
<tr>
<td>Peak</td>
<td>1.54</td>
<td>3.09</td>
</tr>
<tr>
<td>Off-peak</td>
<td>1.54</td>
<td>3.09</td>
</tr>
<tr>
<td>Total</td>
<td>2.84</td>
<td>5.62</td>
</tr>
<tr>
<td>Total passenger-km (mio per day)</td>
<td>98.95</td>
<td>86.62</td>
</tr>
<tr>
<td>Total vehicle-km (mio per day)</td>
<td>56.55</td>
<td>47.80</td>
</tr>
<tr>
<td>Average Speed (km/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>30.08</td>
<td>35.47</td>
</tr>
<tr>
<td>Peak</td>
<td>30.08</td>
<td>35.47</td>
</tr>
<tr>
<td>Off-peak</td>
<td>30.08</td>
<td>35.47</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>23.16</td>
<td>27.31</td>
</tr>
<tr>
<td>Peak</td>
<td>23.16</td>
<td>27.31</td>
</tr>
<tr>
<td>Off-peak</td>
<td>23.16</td>
<td>27.31</td>
</tr>
</tbody>
</table>

results with those in Viton (1983), we present simulation results under the assumption that public transport companies are subject to “Mohring” effects (Mohring, 1972), that is, that at low levels of capacity utilisation they can serve more passengers at little extra cost. A large number of additional simulations were performed (see De Borger et al., 1994, for details). These include restrictions on total demand, allowing for price discrimination between peak and off-peak for the public transport mode only, imposing restrictions on public transport fares, simulations with variable elasticities, and so on. Moreover, a detailed sensitivity analysis was performed with respect to the price elasticities used. These indicated that the optimal prices are sensitive only to the own-price elasticity of the private car. All results are available on request from the authors.
4.1 Basic model: no budgetary nor other restrictions

Assuming that the government can use first-best instruments so that $\lambda = 0$ and $\sigma_h = 1$, optimal transport prices $p^*$ were shown to equal marginal social costs $S^*$ for all modes and periods (see expression (21)). Using the elasticity values previously given we obtain the results reported in Table 4. The first column of the table presents current prices, marginal social costs and average speed of the different transport services. The second column gives the results of the basic model. The third column reports the percentage deviation of the optimal values as compared to the current situation.

First consider the optimal prices. For private transport in both periods and for public transport in the peak period, prices turn out to be substantially higher than current price levels, while optimal prices for public transport in the off-peak period are below current prices. Internalisation of external costs obviously implies that optimal prices are higher in the peak period than in the off-peak period. Note that in the peak period the percentage rise is larger for the car mode than for public transport. In the off-peak period car prices rise, while public transport prices are reduced. Specifically, car prices in the peak rise by 150 per cent as compared to a 30 per cent increase in the off-peak period. Public transport prices decline by more than 43 per cent in the off-peak, and they rise by 22 per cent in the peak period. Finally, note that optimal prices per passenger-km are higher for private transport than for public transport, unlike current prices.

The optimal fare structure causes a 20 per cent decrease at peak car traffic. The drastic increase in the price of peak car use causes a large reduction in demand along the demand schedule which is only slightly compensated by the upward shift in the demand function resulting from the price increases of the relevant substitutes, off-peak car use and peak public transport. The combined effect is a substantial decrease in car traffic in the peak period. Figure 1 illustrates the optimum relative to the current situation.

We find an 11 per cent decrease in off-peak car traffic. This results from the fact that the combination of the own-price effect and the effect of a decrease in off-peak public transport fares is larger than the compensating impact of the increase in peak car prices. We further note a substantial increase in peak bus and tram traffic (100 per cent). This is mainly the result of the price increase of peak private transport. This shifts the demand curve for public transport to the right. Despite the simultaneous demand reduction resulting from the increase in the price of public transport and the decrease in off-peak public transport fares, the combined effect of all price changes is towards more public transport use in the peak period. The 94 per cent increase in off-peak public transport can be explained in a similar fashion.

The ultimate result is a reduction of the total traffic volume, measured in passenger-km, of 12 per cent. Total car traffic decreases by almost 16 per cent, while public transport use increases by 97 per cent. Total peak traffic and total off-peak traffic both decrease.\(^\text{20}\)

\(^{20}\) One could argue that substantial changes in total traffic are somewhat unrealistic because of the captive nature of a substantial fraction of all work trips. To see the implications of restricting overall traffic we therefore also simulated optimal prices assuming that total traffic had to remain constant at its 1989 level. We found lower optimal prices for all modes and periods in that case. Overall car traffic, but especially public transport traffic in the off-peak period, increased markedly. Marginal social costs exceeded the optimal prices for all transport services.
In terms of the environmental impact it is interesting to note that the number of vehicle-km declines by 15 per cent.

As should be the case, all prices equal marginal social costs in the optimum. Note, however, that in comparison with the initial situation, the marginal social costs of all modes and in all periods have been reduced. This finding allows us to emphasise a well-known but important insight: it is not the current level of marginal social costs which should guide optimal price determination, but the level at optimal traffic levels. At the optimum, marginal social costs are well below their values at current traffic volumes.

The marginal social costs associated with peak traffic are reduced more than those associated with off-peak traffic. In both periods, the reduction in marginal social costs is larger for the private transport mode than for the public transport mode. Note that the decline is actually quite substantial (40 per cent) for peak car traffic. The reduction in car use is also responsible for the lower marginal social cost of public transport use: despite higher public transport use its social marginal cost declines because of the lower congestion associated with lower car traffic levels. A final remark relates to average speeds: reduced congestion increases average speed for both transport modes relative to the initial situation, especially in the peak period.

3.2 Pricing restrictions: no difference between peak and off-peak prices
In a second application we impose some direct restrictions on prices to analyse their implications. In reality it is often physically or politically infeasible to charge a different price for peak and off-peak travel. Therefore, we investigated optimal prices under the restriction that no difference between peak and off-peak prices is allowed. The theoretical
Table 5
Simulation Results: Pricing and Budgetary Restriction

<table>
<thead>
<tr>
<th></th>
<th>Basic Optimum</th>
<th>Model without difference between peak and off-peak prices</th>
<th>Model with a budget restriction on the public transport sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal values</td>
<td>Percentage change wrt basic optimum</td>
<td>Optimal values</td>
</tr>
<tr>
<td>Prices (BF per passenger-km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>6.67</td>
<td>4.73</td>
<td>−29.01</td>
</tr>
<tr>
<td>Off-peak</td>
<td>3.46</td>
<td>4.73</td>
<td>36.75</td>
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<tr>
<td>Bus/Tram</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>4.22</td>
<td>1.84</td>
<td>−56.36</td>
</tr>
<tr>
<td>Off-peak</td>
<td>1.95</td>
<td>1.84</td>
<td>−5.67</td>
</tr>
<tr>
<td>Marginal Social Costs (BF per passenger-km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>6.67</td>
<td>7.72</td>
<td>15.73</td>
</tr>
<tr>
<td>Off-peak</td>
<td>3.46</td>
<td>3.36</td>
<td>−2.93</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>4.22</td>
<td>4.29</td>
<td>1.69</td>
</tr>
<tr>
<td>Off-peak</td>
<td>1.95</td>
<td>1.94</td>
<td>−0.59</td>
</tr>
<tr>
<td>Traffic Flow (mio passenger-km per day)</td>
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<td></td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>37.85</td>
<td>41.16</td>
<td>8.72</td>
</tr>
<tr>
<td>Off-peak</td>
<td>43.15</td>
<td>35.53</td>
<td>−17.66</td>
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<tr>
<td>Total</td>
<td>81.00</td>
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</tr>
<tr>
<td>Bus/Tram</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>3.09</td>
<td>2.48</td>
<td>−19.67</td>
</tr>
<tr>
<td>Off-peak</td>
<td>2.52</td>
<td>3.28</td>
<td>30.11</td>
</tr>
<tr>
<td>Total</td>
<td>5.62</td>
<td>5.77</td>
<td>2.70</td>
</tr>
<tr>
<td>Total passenger-km (mio per day)</td>
<td>86.62</td>
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<tr>
<td>Total vehicle-km (mio per day)</td>
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<td>Average Speed (km/h)</td>
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<td></td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>35.47</td>
<td>33.76</td>
<td>−4.84</td>
</tr>
<tr>
<td>Off-peak</td>
<td>45.85</td>
<td>46.61</td>
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</tr>
<tr>
<td>Bus/Tram</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Peak</td>
<td>27.31</td>
<td>25.99</td>
<td>−4.84</td>
</tr>
<tr>
<td>Off-peak</td>
<td>35.31</td>
<td>35.89</td>
<td>1.65</td>
</tr>
<tr>
<td>Multiplier: −0.18</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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pricing results corresponding to this case were developed in the previous section (see equation (23)). The results of this exercise are contained in columns 2 and 3 of Table 5.

Note that optimal car prices are between the optimal peak and off-peak prices of the basic model. The peak price is substantially below the corresponding marginal social cost, while the opposite holds for off-peak car prices. The price of public transport turns out to be approximately equal to the off-peak price in the basic optimum, resulting in a large decline in peak price. Total traffic decreases by almost 5 per cent as compared to the basic optimum. The volume of car traffic decreases by some 5.3 per cent, while public transport traffic rises by some 2.7 per cent. Peak traffic increases by 6.6 per cent, whereas off-peak traffic decreases by 15 per cent. Marginal social costs in the peak period exceed those in the basic model; the opposite holds for the off-peak period.

3.3 Imposing a budget restriction on public transport

To analyse the implications of a formal budget constraint we impose the restriction

\[ FC + \sum_{i=3}^{5} c^i = \sum_{i=3}^{5} p^i \cdot X^i \]  

(28)

on the public transport sector. The optimal pricing rules for this case were given and interpreted in the previous section (see equation (26)). Imposing this restriction, we implicitly assume that the fixed costs remain at their 1989 level.\(^{21}\)

The results of this simulation are reported in columns 4 and 5 of Table 5. We observe that in order to satisfy the budget restriction all optimal prices rise with respect to the base case. Interestingly, note that the budget restriction on the public transport sector also makes car use more expensive. The budget restriction forces the public firm to raise its prices. With non-zero cross-price effects, this in turn implies increasing congestion. To counteract this negative congestion effect optimal private transport prices rise as well.

Note that, as expected, prices are no longer equal to marginal social costs. For the peak and off-peak periods, car and public transport prices exceed marginal social costs.

3.4 Allowing for “Mohring” effects

The simulation models considered so far assume fixed occupancy rates for public transport vehicles. This assumption implies that marginal capacity, congestion, accident and environmental costs are allocated to public transport passengers, such that the marginal cost associated with an additional public transport user is approximated by the marginal cost of a vehicle-km divided by the occupancy rate. Although this procedure is well established in the transport economics literature, it implies that passenger-km and vehicle-km are perfectly correlated. However, relaxing this assumption, it has been

\(^{21}\) The model assumes a fixed occupancy rate for urban transport vehicles. In other words, it is assumed that rolling stock is adjusted according to demand variations. As a consequence, fixed costs (which include expenditures on non-driving personnel, energy costs for infrastructure, expenditures on materials, reparations and deliveries with respect to infrastructure, insurance costs and depreciation expenses other than those for rolling stock (Evard, 1992; and De Borger et al., 1994)) will typically not remain at their observed 1989 level. The budget restriction imposed is used as one simple example among a large number of alternatives to illustrate the impact of budgetary constraints.
Table 6
Simulation Results: Mohring Effects

<table>
<thead>
<tr>
<th></th>
<th>Basic Optimum</th>
<th>Model allowing for Mohring effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal Values</td>
<td>Percentage Change with respect to Basic Optimum</td>
</tr>
<tr>
<td>Prices (BF per passenger-km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>6.67</td>
<td>6.55</td>
</tr>
<tr>
<td></td>
<td>3.46</td>
<td>3.47</td>
</tr>
<tr>
<td>Off-peak</td>
<td>4.22</td>
<td>1.87</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>1.95</td>
<td>1.03</td>
</tr>
<tr>
<td>Marginal Social Costs (BF per passenger-km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>6.67</td>
<td>6.55</td>
</tr>
<tr>
<td></td>
<td>3.46</td>
<td>3.47</td>
</tr>
<tr>
<td>Off-peak</td>
<td>4.22</td>
<td>1.87</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>1.95</td>
<td>1.03</td>
</tr>
<tr>
<td>Traffic Flow (mio passenger-km per day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>37.85</td>
<td>37.20</td>
</tr>
<tr>
<td></td>
<td>43.15</td>
<td>42.53</td>
</tr>
<tr>
<td>Total</td>
<td>81.00</td>
<td>79.74</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>3.09</td>
<td>4.01</td>
</tr>
<tr>
<td>Off-peak</td>
<td>2.52</td>
<td>4.29</td>
</tr>
<tr>
<td>Total</td>
<td>5.62</td>
<td>8.30</td>
</tr>
<tr>
<td>Total passenger km (mio per day)</td>
<td>86.62</td>
<td>88.04</td>
</tr>
<tr>
<td>Total vehicle-km (mio per day)</td>
<td>47.80</td>
<td>47.13</td>
</tr>
<tr>
<td>Average Speed (km/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>35.47</td>
<td>35.79</td>
</tr>
<tr>
<td></td>
<td>45.85</td>
<td>45.90</td>
</tr>
<tr>
<td>Off-peak</td>
<td>27.31</td>
<td>27.56</td>
</tr>
<tr>
<td>Bus/Tram</td>
<td>35.31</td>
<td>35.34</td>
</tr>
</tbody>
</table>

forcefully argued (see, for example, Mohring, 1972; and Turvey and Mohring, 1975) that the marginal cost caused by an additional passenger at low load factors is extremely small. It has been suggested that the marginal cost of a passenger-km, at constant vehicle-km, just equals marginal boarding and alighting time costs. The purpose of a final simulation exercise is, therefore, to analyse what happens to optimal prices if we allow for these “Mohring” effects.
In this final exercise we relax the assumption of fixed occupancy rates in the simplest possible way by assuming that public transport supply remains at its observed level in the reference situation. Moreover, it is assumed that the marginal operating cost associated with additional passengers is zero, and that the marginal boarding and alighting time costs imposed on fellow passengers are the relevant marginal external cost of an extra public transport user. Using 3.6 seconds as an estimate of the time needed to board and unload a passenger (Mohring, 1972), and noting that the average distance travelled by a public transport passenger in Belgian urban areas is approximately 4 km (Boniver, 1992), the marginal boarding and alighting time for an additional passenger-km equals 0.9 seconds. The value of in-vehicle time for public transport users was estimated above at 124BF per hour, implying that the marginal boarding and alighting time costs equal (number of fellow passengers)*0.031BF.

The results of this final simulation are reported in Table 6. As expected, all prices equal marginal social costs in the optimum. As the marginal social costs of public transport are well below the current price levels, there is a substantial (192 per cent) increase in public transport use with respect to the current situation. The decrease in public transport fares and the increase in car prices result in a 17 per cent decrease in private transport use. This situation implies decreasing congestion.

With respect to the basic optimum, allowing for Mohring effects results in much more public transport use (47.88 per cent), but very little difference in private car use (−1.56 per cent). Apart from the fact that the share of public transport is quite small in the basic optimum, this finding may be attributed to two additional causes. First, the cross-price elasticities $\eta_1$ and $\eta_2$ are very small (0.03 and 0.02 respectively). Second, the public transport companies are not allowed to re-optimise service levels so as to reduce waiting time and thereby raise effective bus speed.\(^{22}\)

Two final observations are worth mentioning. First, the results imply notable changes in modal shares. In 1989, about 97 per cent of people travelling were using the private car. In the optimal situation, this figure has dropped to 90 per cent. This modal shift is consistent with results obtained by Viton (1983). He found extreme transit-favouring modal shifts when all pricing and investment decisions are made correctly. Second, despite the extreme assumption on marginal costs of public transport, the optimal situation yields quite reasonable occupancy rates. There are on average 60 passengers on a bus in the peak period and 33 people in the off-peak period.

4. Conclusions
This paper has analysed the introduction of social cost considerations in the pricing of urban transport. We developed a theoretical extension of the Glaister-Lewis model to incorporate external environmental, accident and congestion effects and distributional considerations. We concentrated on the computation of optimal prices for car use and public transport. The level of the marginal social cost of congestion and other externalities

\(^{22}\) We thank an anonymous referee for making this point.
is itself a function of the intensity of car and bus use so that an equilibrium optimum price had to be computed, taking into account demand and supply responses. The application uses aggregate data and therefore ignores distributional issues. It captures the main external effects generated by urban transport activities.

Not surprisingly, ignoring distributional and budgetary considerations, optimal prices were found to equal marginal social costs in the optimum. A model without restrictions yields optimal prices that are substantially higher than observed prices for private transport (150 per cent in the peak period, 30 per cent in the off-peak period) and for public transport in the peak period (22 per cent). In the off-peak period public transport prices decrease by more than 43 per cent compared with the current situation. Optimal prices are higher in the peak than in the off-peak, and in both periods optimal prices are higher for private transport than for public transport. The optimal transport prices cause a substantial increase in public transport use and a 15 per cent decrease in total car traffic.

The results clearly illustrate a simple but important observation. Optimal pricing has to be guided by marginal social costs at optimal traffic levels, which may substantially deviate from social costs at current traffic levels. It is simply incorrect to equate prices to observed marginal social costs, because the level of the marginal social cost of congestion and other externalities is itself a function of the intensity of car and bus use.

A number of additional simulations were performed to investigate the effects of different restrictions on prices. First, introduction of a budget restriction for the public transport authority yields higher optimal prices for all modes and periods. Specifically, public transport prices rise by more than 115 per cent in the peak and by more than 30 per cent in the off-peak, compared to the basic model. Percentage rises in car prices are more moderate. These price rises cause all traffic levels to decrease with respect to the optimal situation without restrictions. Car traffic decreases by 1 per cent, while public transport traffic decreases by 16 per cent. Second, assuming that for political or technical reasons price discrimination between peak and off-peak periods is difficult, we obtained peak prices for both private and public transport that are substantially lower than the corresponding marginal social costs. Car traffic would be reduced by some 5 per cent as compared to the basic model, public transport use would increase somewhat. Finally, making due allowance for Mohring effects (that is, very low marginal costs at low occupancy rates) leads to an expected substantial rise in public transport volume, and a corresponding decline in congestion.

Appendix

Determination and Valuation of the Marginal External Costs

The marginal external air pollution costs of urban transport were determined in two consecutive steps. First, the emissions per car-km were calculated; in a second step the monetary valuation of these emissions was estimated. Because of data limitations, the analysis had to be limited to the emissions of nitrogen oxides (NOx), sulphur dioxide (SO2), carbon dioxide (CO2) and hydrocarbons (HC). The emission factors per vehicle-
km are based on CONCAWE (1986), Cuijpers (1992), Econotec (1990) and Zierock et al. (1989).

For the monetary evaluation of the emissions per vehicle-km we extensively used the results of Mayeres (1992, 1993). These studies point to two important problems associated with the direct measurement of the marginal costs of pollution. First, evaluation of the effects of marginal emissions would ideally require information on the impact of emissions on the concentration levels of the different primary and secondary air pollutants concerned. This necessitates the use of dispersion models to predict the spread of the pollutants and transformation models that describe the interaction of different pollutants to form secondary pollutants. Unfortunately, such quantitative models are not yet fully operational. Second, the existing international literature on the monetary evaluation of air pollution (see, for example, Nordhaus, 1991), produces a wide range of numerical results, and these cannot easily be transferred to a Belgian situation. Therefore two different, indirect, approaches were used to approximate the monetary value of marginal emissions of air pollutants. The first was used for the monetary valuation of NOx, SO2 and HC emissions, while the second concerned the valuation of CO2 emissions. The difference in approach was motivated mainly by a difference in available information.

The air pollution problems associated with the emissions of SO2, NOx and HC have an important and non-negligible international dimension; emissions in Belgium do not only have an impact on the Belgian territory but also affect other countries. When trying to evaluate the damage from air pollution, two attitudes are possible. Either one approaches the problem from the point of view of a non-cooperative country which only takes into account the damage on its own territory, or one also considers the damage for the other countries. The latter case may be called a cooperative approach. Considering the fact that Belgium has adhered to international conventions on the control of SO2, NOx and HC, the cooperative approach seems to be called for and therefore has been used in this analysis. The methodology for evaluating SO2, HC and NOx emissions starts from the emission reduction objectives for the different air pollutants, based on existing international agreements which Belgium has signed (see Mayeres, 1993, for more details). Using information on different abatement techniques, their abatement potential and their unit reduction costs, one can calculate the effect on the abatement costs if one has to reach these objectives and an extra vehicle-km generates additional emissions. This difference in abatement costs is then used as a proxy for the marginal external air pollution costs. Note that this approach makes a number of important assumptions. It assumes that there are no indivisibilities in the emission abatement possibilities and that the abatement techniques are used in a cost-effective way, that is, the cheapest technologies are used first. Moreover, it is assumed that the air pollution damage does not depend on the place or time of the emissions. Finally, it is also clear that the results are to a large extent affected by the emission reduction objectives put forward.

The methodology for evaluating CO2 emissions is different from the one described previously, but also looks at the problem in a cooperative way. CO2 emissions are at the basis of world-scale environmental problems. One therefore has to decide whether one takes account of the increased damages at world level, EU level or national level. The
approach chosen in Mayeres (1993) values increases in CO₂ emissions at the total marginal damage at the EU level. A similar approach is used by Proost and Van Regemorter (1995). The energy carbon tax of $10 per barrel of oil proposed by the EU is interpreted as the marginal willingness to pay of the EU for a reduction in CO₂ emissions (see also Nordhaus, 1991). The resulting marginal air pollution costs associated with the use of a private car are estimated to be 0.6018BF per km. The corresponding figure for public transport is 2.346BF per vehicle-km.

Concerning the marginal external noise costs, the exercise only takes into account those caused by public transport. The values are taken from Boniver (1993). She reports 3.45BF and 9.34BF for the peak and the off-peak periods respectively. She first determines the effect of an additional vehicle-km by public transport on the noise level, and then expresses the change in the noise level in monetary terms based on a variety of existing hedonic price studies for traffic noise (see, for example, Nelson, 1982; Pearce and Markandya, 1989; and Alexandre and Barde, 1987).

Estimates for the marginal external accident costs have been based on the results of Mayeres (1993) and Boniver (1993). They apply the methodology proposed by Jones-Lee (1990) to car and public transport in Belgium. Three types of possible marginal external accident costs are discerned: (i) those associated with the risk of death or injury to the occupants of an additional car or public transport vehicle; (ii) those associated with the increased risk to other motorised road users; and (iii) those associated with the increased risk to pedestrians and bicyclists. The second category has to be included if an additional vehicle-km changes the probability that other motorised road users are involved in accidents. In our paper we have assumed that this is not the case and that the ratio of the marginal to the average accident ratio equals unity. An important input into the calculation of the marginal external accident costs is the value of a statistical life or statistical injury. Our results were obtained using the findings of Jones-Lee (1990) and O’Reilly et al. (1992). This finally yields a marginal accident cost for car use of 1.6145BF per km. The external accident costs caused by an additional public transport-km are calculated to be 7.5286BF.

References
Optimal Pricing of Urban Passenger Transport

B. De Borger et al.


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