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Optimal urban transport pricing in the presence of congestion, economies of density and costly public funds

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Abstract

Using a numerical model of the urban transportation sector, calibrated to data for Brussels and for London, we calculate the optimal transport price structure and its effect on the transport equilibrium and on welfare. Removing existing subsidies to public transport and to car parking, internalising transport externalities (mainly congestion) and optimizing the frequency of public transport service increases welfare by approximately 2% of total income in both cities. Optimal prices are higher than current prices in most transport markets, so that optimal transport demand is below current demand. There is a strong shift to public transport in the peak period. Finally, calculations for Brussels of optimal public transport prices for unchanged reference car taxes indicate that only limited welfare gains can be obtained by charging near-zero fares in peak hours.

JEL: H21, H23, R41, R48

Keywords: Transport, congestion, public transport

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1. Introduction

As is clear from a considerable amount of theoretical and empirical research, current urban transport prices do not reflect the marginal social costs of transport. There are several explanations for the divergence. First, prices usually fail to reflect marginal external costs of, mainly, congestion, accidents, air and noise pollution, and road wear. Second, public transport often receives subsidies that are not justified on cost grounds. Third, the costs of parking are imperfectly mirrored in prices, e.g. when it is provided for free. Of course, the mere existence of deviations between prices and marginal social costs does not directly imply that prices are wrong, as deviations are justified when there are pricing constraints in the transport sector or when distortions exist in other sectors. Nevertheless, many studies find that welfare-improving pricing reforms are possible, and that taking better account of the above mentioned cost elements is a major component of such reforms.

This paper studies the effects of introducing optimal urban transport prices in Brussels and in London, focussing on the contribution of externalities, economies of density and non-transport related inefficiencies to the optimal price structure and its effects. Internalising congestion externalities is seen to be crucial, but optimal revenue use has a substantial effect on the price structure and the resulting equilibrium as well. We pay specific attention to the derivation of optimal public transport prices. It has long been recognised that subsidies to public transport are justified because of economies of density (cf. the seminal paper by Mohring, 1972): higher demand levels in a given geographical area imply reduced average social costs of a public transport trip, because larger vehicles can be used, or the frequency of service can increase, or the route structure can be made denser.[1] We find that economies of density are of non-negligible importance in determining optimal urban transport prices, but

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[1] It is not always true that subsidies are justified because of decreasing average operator costs (cf. Berechman,

that they are quantitatively less important than the negative externalities and than the considerations of revenue use. Our assessment of the role of public transport within the optimal urban transport system is more moderate than that of Viton (1983), where optimal pricing implies that public transport becomes the dominant mode, and Winston and Shirley (1998), where it virtually disappears; the results are broadly consistent with those of De Borger and Wouters (1998) and Parry and Small (2002).

The available urban transport pricing studies differ in terms of the amount of spatial, temporal and modal detail in the representation of urban transport, as well as in the transport cost components that are taken into account. At one extreme, there are one-period models focussing on one mode and a single inefficiency (mostly peak car use under congested conditions); at the other extreme are multi-modal and multi-period network models of the urban transport system. Studies also differ in the extent to which imperfections inside and outside the transport sector are modelled. At one end are the partial equilibrium models, here defined as models where marginal social cost pricing produces optimal welfare when there are no pricing constraints in the transport sector; at the other end, there are full-fledged general equilibrium models that focus on the interaction between transport pricing and inefficiencies in the rest of the economy. While general equilibrium approaches do not deny the importance of prices that reflect external costs, they do suggest that existing tax distortions outside transport have large effects on optimal transport prices and on their welfare potential.[2]

This paper is based on a model of intermediate complexity. The urban transport system is represented by some twenty transport markets; this allows distinguishing the main dimensions of transport demand and costs. Economies of density in public transport are taken

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1993).

[2] E.g., Mayeres and Proost (1997) find that, while optimal prices are fairly insensitive to the degree of inequality aversion, optimal revenue use changes from labour tax reductions to lump sum redistribution when inequality aversion increases. Van Dender (2003) emphasises that, when commuting is a strict complement to labour

into account through the dependency of waiting times on the supply of bus and metro kilometres. As such, the model is a partial equilibrium model of the urban transport system. The numerical version allows taking account of pricing constraints in the transport sector, so that second-best prices can be explicitly computed and the welfare cost of pricing constraints can be assessed. The role of costly public funds is studied by varying the weight that is given to the net transport revenues. The model is sufficiently detailed to provide strategic policy guidelines, yet simple enough to allow intuitive interpretation of the numerical results.

The structure of the paper is as follows. Section 2 provides a largely intuitive discussion of the modelling approach, focussing on the interaction between congestion, economies of density, and non-zero shadow values for tax revenues. Section 3 discusses the properties of the numerical model and the characteristics of the reference equilibrium in Brussels and in London to which it is calibrated. Section 4 presents the effects of implementing optimal transport prices, paying particular attention to the impact of economies of density and tax revenue premiums. Section 5 deals with the second-best case of optimal public transport prices for non-optimal car prices. The effect of introducing optimal prices on the public transport budget is briefly discussed in section 6. In section 7, we compare our results to those obtained in earlier studies. As was remarked by a referee, "the findings of the other studies […] are quite disparate, running the gamut from very low optimal transit fares and huge market shares to higher fares with lower shares". While a systematic comparison is not possible, as our model is not an encompassing one, we can explain the main causes for the differences between different analyses. Finally, section 8 concludes.

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supply, it may be optimal to charge commuting trips well below marginal social costs.

2. Modelling approach

The case study results presented in the next sections are based on a two-period multimodal model of the urban transport system. Here, we explain the logic underlying that model in the simple context of a car mode and a bus mode that are available in peak hours, and that are subject to congestion. Bus transport is characterised by economies of density. Including more transport markets and externalities requires no conceptual extensions; relevant numerical detail is supplied in section 3.

We look for prices that maximize the social welfare function given in (1), using car taxes t_c and bus fares t_b. Car demand q_c and bus demand q_b are expressed in passenger-kilometres; X_b is the supply of bus-kilometres. V is the indirect utility function of a representative consumer, expressed as a function of generalised prices of car transport and bus transport; a is the in-vehicle travel time (assumed to be equal for cars and buses), z_b is the waiting time for buses at the stop, c_c is the constant marginal cost of a car-kilometre, and c_b is the constant marginal cost of supplying a bus-kilometre. As can be seen in (1), social welfare is the sum of a utility term and a government revenue term. The indirect utility function has an income term that consists of exogenous income Y (including income from fixed labour supply) and net tax revenue from the transport sector. Indirect utility is translated into money terms by dividing it by the marginal utility of money; λ_r is the marginal utility of income in the reference equilibrium. The second term of the welfare function reflects the extra gain that is obtained from using the net transport tax revenue for reduction of other taxes rather than recycling it as lump sum income; μ is the marginal social value of transport tax revenue, minus one.

$$\frac{1}{\lambda_r} V\left(c_c + t_c + a, t_b + a + z_b, Y + t_c q_c + t_b q_b - c_b X_b\right) + \mu\left(t_c q_c + t_b q_b - c_b X_b\right) \tag{1}$$

Bus transport is supplied by the social welfare-maximiser. The representation of the bus sector assumes proportionality between the supply of bus-kilometres and bus-passenger-kilometres; this implies that $X_b = \beta q_b$, where β is the inverse of the occupancy rate.[3] Substituting this constraint in (1), taking first-order conditions with respect to t_c and t_b and rearranging, leads to the implicit expressions for car taxes and bus fares in (2) and (3), respectively. In these equations, $\alpha \equiv {}^{\mu}\!/_{\tilde{\lambda} + \mu}$, where $\tilde{\lambda} \equiv {}^{\lambda}\!/_{\lambda_r}$; $\left(a' \equiv {}^{\partial a}\!/_{\partial F} \right) > 0$, where $F \equiv q_c + X_b$; $\left(z'_b \equiv {}^{\partial z}\!/_{\partial X_b} \right) < 0$.

$$
\begin{aligned}
t_c = {} & \alpha \frac{q_c}{\left| {}^{\partial q_c}\!/_{\partial t_c} \right|} + (1-\alpha) a'(q_c + q_b) \\
& - \left(t_b - \beta \left(c_b + (1-\alpha)\left(a'(q_c + q_b) + z'_b q_b \right) \right) \right) \frac{{}^{\partial q_b}\!/_{\partial t_c}}{{}^{\partial q_c}\!/_{\partial t_c}}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
t_b = {} & \alpha \frac{q_b}{\left| {}^{\partial q_b}\!/_{\partial t_b} \right|} + (1-\alpha) \beta \left(a'(q_c + q_b) + z'_b q_b \right) \\
& - \left(t_c - (1-\alpha) a'(q_c + q_b) \right) \frac{{}^{\partial q_c}\!/_{\partial t_b}}{{}^{\partial q_b}\!/_{\partial t_b}}
\end{aligned} \tag{3}
$$

To ease interpretation, first assume that the private and social marginal value of income are equal ($\mu = 0$), so that $\alpha = 0$. In that case, the car tax and the bus fare equal the

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[3] In principle, when bus operations are publicly owned, bus supply levels become an instrument in maximising social welfare as well (cf. De Borger and Wouters, 1998, for an explicit treatment). However, we assume that government sets bus supply at the lowest possible level corresponding to a given level of demand (the technical minimum). This reflects the hypothesis that the marginal social benefits of expanding supply above the technical minimum are below the marginal social costs of doing so. Specifically, in our model waiting time reductions are socially less valuable at the margin, than increases in congestion and operating costs. By the additional assumption that the technical minimum supply ratio, expressed as the ratio of bus-kilometres to bus-passenger-kilometres, is independent of demand volumes, bus occupancy rates are constant.

respective marginal external time costs, as given by the second term on the right hand sides.[4] For cars, only the marginal external congestion cost matters; for buses, the waiting time cost reduction also enters the expression, and bus-kilometres are converted to passenger-kilometres by β.

Next, when cross-price effects are zero, but $\alpha > 0$ (i.e. there is a positive weight for transport tax revenues[5]), the first two terms on the right hand sides matter. These terms refer to the revenue-raising function of the transport taxes. Raising revenue in the transport sector becomes more attractive as the revenue becomes socially more useful (increasing α), and the extent of revenue-raising in a particular market is determined by the inverse of the own-price effect. The importance of the second term, referring to the externality, correspondingly decreases. Finally, when cross-price effects are positive (i.e. when cars and buses are substitutes) and $\alpha > 0$, the last term on the right hand side co-determines the taxes. Deviations between taxes and marginal external costs on the other market then affect the tax on the own market. This effect is likely to be small, except for the public transport market when the cross-price effects are large and car prices are very inefficient.

Extension of this basic set-up to the more detailed model of the next section is easy. The same type of tax rule will hold for each market. That is, taxes in each market are mainly determined by the relevant external costs in that market, and by the extent to which the market allows revenue-raising without causing excessive inefficiencies. We now turn to a description of the numerical implementation.

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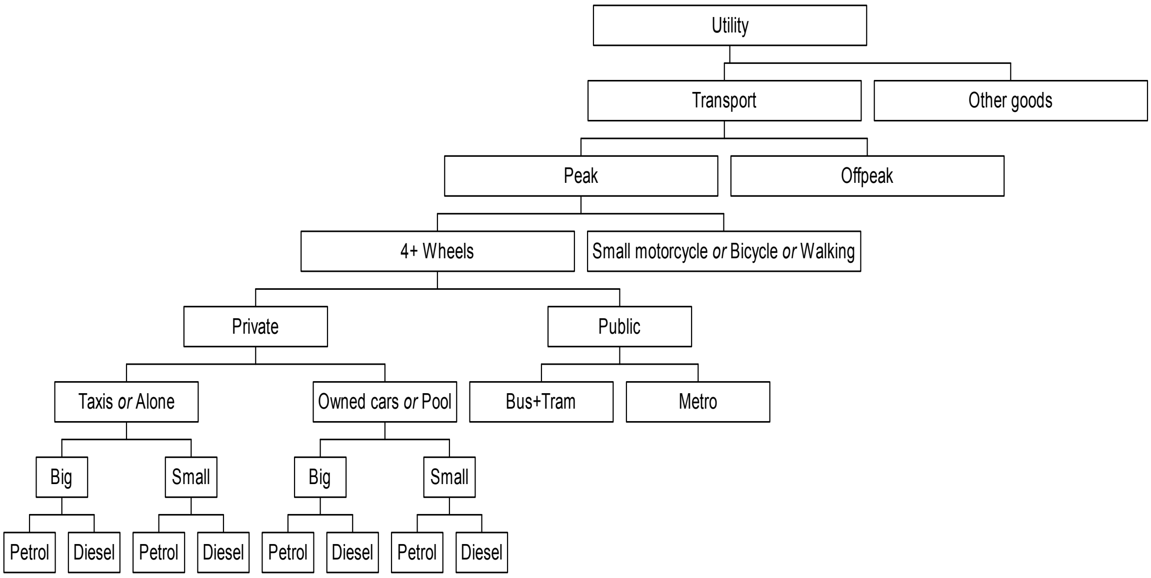
[4] This is true whether cross-price elasticities are zero or not.

[5] Negative weights are conceivable as well, but they are not discussed in this paper.

3. Numerical implementation and reference equilibrium

Instead of distinguishing between just two markets, the urban transport system is now represented by many transport markets. The demand side is an aggregated representation of the choices of transport users. Demand for passenger transport is generated by assuming that a set of representative individuals optimally allocate their generalised income between passenger transport and other goods. Many passenger transport services are available: motorised and non-motorised transport, peak and off-peak travel, cars or one of the available public transport modes. For Brussels, metro and tram or bus are distinguished. The London case study distinguishes bus, metro and rail transit. For passenger car transport, different types and sizes of vehicles are available. These vehicles differ in terms of user costs and environmental impacts. Finally, the individual has the explicit options of driving solo or car-pooling. The structure contains 20 alternative transport markets in total, all of which vary in terms of resource costs, external costs, taxes and substitutability. Demand for each type of transport service in a given geographical zone is a function of the generalised price of that type of transport service (this is the sum of money price and time cost), of the generalised prices of the other transport services and of other factors (like income and preferences). Demand for each consumer group is modelled by a nested CES function, of which the nesting structure is depicted in Figure 1.

Figure 1 Nested CES implementation in the TRENEN model



In the equilibrium price module, generalised prices are computed for the different types of transport services. The generalised price is the sum of three elements: (a) the producer price for different types of vehicle km, (b) the transportation time cost consisting of in-vehicle time, walking and waiting time, and (c) a tax (or subsidy) that has two policy functions: to raise tax revenue or subsidise certain modes of transportation, and to correct for external costs of air pollution, marginal congestion costs, noise and accidents.

The model is calibrated for a given reference equilibrium (here, Brussels and London in 2005) using observed or forecasted money prices and quantities for all transport modes for a representative day of the year, together with information on the ease of substitution between transport and other goods as well as between the different means of transport.[6] Other important inputs are the structure of resource costs of private and public transport, the external costs and the network congestion function. The network congestion function summarises the

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[6] The model uses nested CES utility functions, where elasticities of substitution for each nest determine ease of

available network information on the relation between volume of road transport and average speed (O'Mahony et al., 1997). The model is static: it represents the equilibrium for a representative day in a given year and assumes that the stock of all means of transport (private and public) is adapted to the demand for transport. The road infrastructure and public transport infrastructure (e.g. the rail network) are kept fixed. The marginal social costs of trips consist of vehicle ownership and operating costs (including parking costs in the case of cars), time costs and the external costs of accidents, air pollution and noise.[7] All external costs except congestion are assumed to be independent of traffic volumes. Transport prices consist of internal costs and taxes. The time costs of travel are the product of travel times and a constant marginal value of time-savings. While car travel times consist of in-vehicle travel times, those for public transport include in-vehicle-time, walking time to the stop and waiting time at the stop. Including walking time improves the accuracy of the calibration, but it is kept constant throughout the different simulations. Waiting time is set equal to half the headway, so it depends on the frequency of service. The latter, in turn, is proportional to the level of public transport demand in the relevant market (constant occupancy rates), so that economies of density result. We do not, however, assume that waiting times decrease in proportion to bus-kilometres; instead, they are proportional to the square root of service.[8]

The numerical model is different from the simple analysis in Section 2 in that it distinguishes between four consumer groups (that all have a nested CES utility structure), on the basis of two criteria: transport users that live inside or outside the urban area under study, and car users that do or do not pay for parking at their destinations. The distinction is not made to allow for distributional analysis (all four groups have the same social welfare

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substitution and price elasticities in a given equilibrium.

[7] Road wear externalities are excluded, given their relatively small importance in an urban context.

[8] This implies that waiting times reduce less than proportionally with demand. For the range of public transport demand changes considered in the numerical applications, the quantitative difference between proportionality

weight), but rather to improve the quality of the calibration. Trip lengths differ between those living inside and outside the area, and this affects per-kilometre costs and prices in a number of transport markets (e.g. when public transport fares are not distance dependent, and when parking costs are taken into account). Obviously, trip costs also differ between car users that do and do not pay for parking.

Finally, the simulations in the next sections use two values for the tax revenue weight (μ)[9] per case study. First, it is set at zero in both cases. This turns the model into a pure partial equilibrium tool. Second, we use a value of 6.6% for Brussels and 3.5% for London. The basic assumption underlying these values is that the transport tax revenue increases will be used to reduce labour taxes, for a constant level of total government revenues. Since transport taxes are paid by both workers and non-workers, this way of using the revenues implies shifting the tax burden from workers to non-workers. Consequently, workers' real wages increase. So, the values are essentially obtained by multiplying the marginal cost of raising 1 Euro of tax revenue, by one minus the share of labour income in total income.[10] The lower value for London reflects lower marginal labour tax rates in the UK as compared to Belgium. Proost and Van Dender (2001) explain in detail how the precise values are obtained.

Table 1 shows the cost and price structure for the reference equilibrium in Brussels and London.[11] For cars, if the value in column E (tax per passenger-kilometre) is as large as the marginal external cost (reported in column D), then the price of transport internalises the

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and the square root rule is small.

[9] The weight equals marginal social value of transport tax revenue minus one, because the nominal value of the tax revenue is already counted as an income change in the utility function.

[10] This is obviously a short cut for a more complex mechanism. Two other factors that could be taken on board in the computation of the MCPF are the direct effects of increased transport prices on the purchasing power of the net wage and the indirect effects of changed commuting costs (public transport and car transport) on the supply of labour (see Parry and Bento, 2001); Van Dender, 2003)

[11] Further detail on the construction of the reference cases is in Proost and Van Dender (1998), Van Dender

external costs and only the revenue-raising objective may justify an extra mark up, at least when drivers pay for parking. For public transport, the money price is the fare, and this should cover marginal operating costs and marginal external costs.

Table1 Reference prices and social costs, Brussels, London, 2005 (Euro/pkm)

			A	B	C	D	E
Brussels			Money price	Generalised price	Marginal external congestion cost	Total marginal external cost	Tax
Car*	Peak	Paid parking	0.474	0.855	2.232	2.323	0.093
		Free parking	0.304	0.685	2.232	2.323	0.093
	Off-peak	Paid parking	0.466	0.613	0.003	0.097	0.087
		Free parking	0.296	0.443	0.003	0.097	0.087
Transit	Bus, tram	Peak	0.120	0.924	0.112	0.320	0.016
		Off-peak	0.120	0.773	0.001	0.579	-0.150
	Metro	Peak	0.120	0.877	0	0.002	0.024
		Off-peak	0.120	0.934	0	0.0009	-0.09
London			Money price	Generalised price	Marginal external congestion cost	Total marginal external cost	Tax
Car*	Peak	Paid parking	0.925	1.267	0.445	0.536	0.118
		Free parking	0.325	0.667	0.445	0.536	0.118
	Off-peak	Paid parking	0.913	1.152	0.035	0.130	0.108
		Free parking	0.313	0.552	0.035	0.130	0.108
Transit	Bus, tram	Peak	0.127	0.893	0.068	0.710	-0.02
		Off-peak	0.113	0.854	0.005	0.406	-0.01
	Metro	Peak	0.153	0.822	0	0.0005	0.095
		Off-peak	0.124	0.938	0	0.001	0.093

*We take the example of a small gasoline car with one occupant, who is a city inhabitant. The model distinguishes between several car types, and between inhabitants of and commuters to the city.

The main causes of deviations between marginal social costs and prices in car markets are easily identified. First, peak period prices for cars do not reflect marginal external congestion costs. Second, free parking constitutes a large subsidy to car use. Free parking is available for an estimated 70% of car users in both case studies. With respect to public transport, the case of Brussels shows that prices more or less cover variable resource costs during peak hours, while large subsidies are given for off-peak transit. For bus and tram we include marginal external congestion costs as these modes delay other traffic. The congestion cost per passenger of a bus is much smaller than that of a car because the higher occupancy of a bus compensates the higher external congestion cost of the bus-kilometre. In London, buses

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(2001) and Peirson et al (2001).

are subsidised in peak and off-peak periods, while metro is not, as is seen from the last rows in Table 1.

Note that peak period congestion costs are higher in Brussels than in London, while the reverse holds for off-peak hours. The Brussels network congestion function is very steep at high traffic levels, and relatively flat at low levels. The London function shows less change in slope as traffic levels rise.[12] Also, observe that parking costs per kilometre are much higher in London than in Brussels, reflecting higher opportunity costs of land, while other resource cost components of car use are of similar magnitude.

The reference waiting times for public transport range from 5 to 7.5 minutes per trip during peak hours, and from 7.5 to 10 minutes in the off-peak.[13] Walking times are of the same order of magnitude; they are somewhat longer on average for metro than for buses, given that metro networks are less extensive.

4. The main effects of optimal transport prices in Brussels and London

As can be seen from Table 2, implementing the optimal price structure in the urban transport system of Brussels and London increases welfare by approximately 2%.[14] This is comparable to earlier studies (e.g. De Borger et al., 1997 and Winston and Shirley, 1998). The driving force behind the gains is the reduction in peak-period traffic flows – with the associated travel speed increases – after the internalisation of the congestion externality (cf. Table 3). However, omitting the inefficiencies of providing free parking is important as well.

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[12] The difference can be attributed to the difference in geographical scope between both cases. The Brussels application considers the central area within the outer ringroad. This is a small and dense urban region, served by a dense transit network. The London case study is more extended geographically, as it takes account of areas adjacent to the business centre (Greater London).

[13] De Borger and Wouters (1998) find average waiting times of 7.2 min and 12.6 min in peak and offpeak hours, for Belgium. Our values are somewhat lower as they refer to a regional context, instead of an urban one. The changes in waiting times that we consider are not very large, so that we stick to the 'wait is half the headway' rule; with large changes, it is better to assume that passengers consult published schedules.

[14] This is a percentage of generalised income, which has the dimension of national income of the region plus the

Proost and Van Dender (2001) show that introducing resource cost pricing of all parking spots, instead of providing 70% of them for free, generates approximately 30% of the welfare gain from fully optimal pricing in Brussels.[15] The welfare increase from internalising non-congestion externalities is relatively less important.

Table 2 Percent welfare gains from optimal urban transport prices, with respect to reference situation

	Brussels		London	
	No tax premium	Tax premium 6.6%	No tax premium	Tax premium 3.5%
No economies of density	1.80%	2.47%	2.02%	2.55%
Optimised service frequency	1.92%	2.50%	2.21%	2.69%

Table 2 also shows that taking account of both economies of density and optimal revenue use leads to a substantial increase in the estimated welfare gains (approximately 0.7%-point in both case studies). The tax premium is more important than economies of density, however, and the contribution of economies of density is smaller when the tax premium is positive. The reason for the latter is that the efficiency gains in transport as such stand for a smaller part of the welfare gain when reductions in distortionary non-transport taxes are taken into account, so that that economies of density are exploited to a smaller extent when public funds are costly. In other terms, the opportunity cost of realising efficiency gains in the public transport market via fares below the marginal resource cost (necessary to generate the positive external economies of density) becomes much larger when tax revenue has a premium. Note that the size of the tax premium in Brussels nearly prohibits the realisation of extra welfare gains via lower waiting times.

Table 3 provides an overview of the main changes in the urban transport system following the implementation of optimal prices. Introducing optimal prices reduces peak period flows by approximately 20% in both cities, and this leads to travel speed increases of more than 40% in Brussels and nearly 15% in London. Because of the increase in the modal

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monetary value of leisure time. So 2% is not a small amount.

[15] We have not computed a comparable scenario for London. However, given the less steep congestion function

share of public transport by some 10% during peak hours, trip demand reductions are smaller than flow reductions. In off-peak hours in Brussels, congestion is virtually non-existent. Reducing the large reference subsidies to public transport in Brussels leads to a decrease of the public transport share. In London, however, public transport shares increase during off-peak hours.

Table 3 Welfare and traffic flow characteristics, reference, optimal pricing without and with economies of density, Brussels, London, 2005 (μ is the tax revenue premium)

Brussels		Reference equilibrium	No economies of density		Positive economies of density	
			$\mu=0$	$\mu=6.6\%$	$\mu=0$	$\mu=6.6\%$
% change traffic flow (pcu)	Peak	0	-20	-22	-21	-23
	Off-peak	0	-3	-12	-7	-15
% change in travel time per km	Peak	0	-44	-45	-46	-47
	Off-peak	0	-0.1	-0.1	-0.2	-0.1
Modal split (%)						
Peak	Car	67	59	61	55	57
	Bus and tram	19	23	22	24	24
	Metro	14	18	17	21	19
	Total	100	100	100	100	100
Off-peak	Car	80	82	82	81	81
	Bus and tram	13	9	9	9	9
	Metro	7	9	9	10	10
	Total	100	100	100	100	100
London		Reference equilibrium	No economies of density		Positive economies of density	
			$\mu=0$	$\mu=3.5\%$	$\mu=0$	$\mu=3.5\%$
% change traffic flow (pcu)	Peak	0	-17	-19	-19	-20
	Off-peak	0	-11	-14	-13	-16
% change in travel time per km	Peak	0	-14	-15	-15	-16
	Off-peak	0	-1	-2	-1	-2
Modal split (%)						
Peak	Car	74	66.0	67	63	64
	Bus and tram	11	9.2	9	9	9
	Metro	15	24.7	24	27	27
	Total	100	100	100	100	100
Off-peak	Car	79	75	75	72	72
	Bus and tram	12	11	11	12	12
	Metro	9	14	14	17	17
	Total	100	100	100	100	100

Table 3 also shows the effects of taking account of economies of density and of introducing a tax premium on the resulting transport equilibrium. During peak hours, allowing for economies of density leads to a further increase of the modal share of public

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and the higher opportunity cost of land, the relative gain from this policy is likely to be higher than in Brussels.

transport, by 4%-point in Brussels and 3%-point in London. In the off-peak, economies of density mitigate the effect of reducing the large reference subsidies in Brussels; in London, they lead to a further increase of public transport shares. Introducing a premium for transport tax revenues (6.6% in Brussels and 3.5% in London) has no large impact on modal split or on peak period demand levels, but it causes a major reduction in off-peak transport demand in Brussels (-15% instead of –7%). This is because off-peak transport is suitable for raising tax revenue. In London, the marginal cost of public funds is lower, leading to a smaller impact on off-peak flows. Finally, as could be expected on the basis of Table 2, the interaction between economies of density and the tax premium mainly implies that the impact of economies of density becomes smaller, so that the modal share of cars is higher in the scenarios with positive tax revenue premiums.

Tables 4 and 5 provide information on the impact of optimal pricing on waiting times, money prices and generalised transport prices, for Brussels and for London respectively. The top half of each table gives the reference prices, which are the same whether economies of density are accounted for or not. The bottom half gives the optimal prices in case economies of density are not (left) and are (right) taken into account. Within each cell in the lower half, we distinguish optimal prices for the case of zero and positive tax revenue premiums.

When no economies of density are taken into account and there is no premium for transport tax revenues, optimal pricing implies substantial money price increases for all modes in peak periods. These higher money prices are mainly caused by the internalisation of the congestion externality, and they are partially offset by lower time costs. The off-peak price increases for buses are large in Brussels, which is the consequence of very high subsidies to off-peak bus transport in the reference equilibrium. The London data show considerable subsidies to bus transport in both time periods in the reference equilibrium. These subsidies are eliminated in the first best optimum.

Attaching a positive premium to tax revenues further increases transport prices, both in money and in generalised terms. Endogenising waiting times moderates the generalised price increases for public transport, in both cities and time periods. Higher demand implies lower waiting times, and the fare increases are smaller in order to internalise the positive waiting time externality. These effects are most clearly observed in metro markets. Metro, which is congestion free, becomes cheaper in terms of time and money during peak hours in both cities.[16] However, waiting times do not decrease in all markets: bus waiting times increase in the off-peak period in Brussels and in both periods in London. The reason is that getting rid of the excessive reference subsidies reduces demand, therefore service frequency and waiting times.

With endogenous waiting times, the effect of introducing a positive tax revenue weight on money prices is more moderate, but it remains substantial. The interaction between the premium and waiting is small, because the premium strongly affects price levels but not relative prices. The attractiveness of public transport is not fundamentally modified by the tax revenue premium. Finally, we note that money prices and generalised prices of car transport are less affected by endogenising waiting times, suggesting that the interaction between economies of density of public transport and road congestion is limited.

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[16] This may no longer hold when account is taken of crowding externalities (Kraus, 1991).

Table 4 Transport prices in the reference situation and in counterfactual equilibria, Euro/pkm, Brussels, 2005 (consumer group = inhabitants paying for parking)

		Reference					
		No economies of density			Economies of density		
		Waiting time	Money price	Generalised price	Waiting time	Money price	Generalised price
Peak hours							
	Car	-	0.47	0.85	-	0.47	0.85
	Bus	1.14	0.12	0.92	1.14	0.12	0.92
	Metro	1.14	0.12	0.88	1.14	0.12	0.88
Off-peak hours							
	Car	-	0.47	0.61	-	0.47	0.61
	Bus	1.7	0.12	0.77	1.7	0.12	0.77
	Metro	1.7	0.12	0.93	1.7	0.12	0.93
		Tax revenue premium = 0; Tax revenue premium = 6.6%					
		No economies of density			Economies of density		
		Waiting time	Money price	Generalised price	Waiting time	Money price	Generalised price
Peak hours							
	Car	-	1.13; 1.65	1.35; 1.86	-	1.08; 1.57	1.29; 1.78
	Bus	1.14	0.43; 0.96	1.08; 1.59	0.98; 1.03	0.32; 0.75	0.93; 1.36
	Metro	1.14	0.20; 0.70	0.96; 1.45	0.93; 1.00	0.09; 0.50	0.81; 1.23
Off-peak hours							
	Car	-	0.54; 0.89	0.69; 1.04	-	0.54; 0.88	0.69; 1.03
	Bus	1.7	0.98; 1.77	1.63; 2.42	2.05; 2.15	0.77; 1.47	1.49; 2.20
	Metro	1.7	0.35; 0.95	1.16; 1.77	1.46; 1.55	0.19; 0.68	0.96; 1.47

Table 5 Transport prices in the reference situation and in counterfactual equilibria, Euro/pkm, London, 2005 (consumer group = inhabitants paying for parking)

		Reference					
		No economies of density			Economies of density		
		Waiting time	Money price	Generalised price	Waiting time	Money price	Generalised price
Peak hours							
	Car	-	0.925	1.27	-	0.925	1.27
	Bus	1.14	0.13	0.89	1.14	0.13	0.89
	Metro	1.14	0.15	0.82	1.14	0.15	0.82
Off-peak hours							
	Car	-	0.913	1.15	-	0.913	1.15
	Bus	1.7	0.11	0.85	1.7	0.11	0.85
	Metro	1.7	0.12	0.94	1.7	0.12	0.94
		Tax revenue premium = 0; Tax revenue premium = 3.5%					
		No economies of density			Economies of density		
		Waiting time	Money price	Generalised price	Waiting time	Money price	Generalised price
Peak hours							
	Car	-	1.28; 1.65	1.57; 1.94	-	1.26; 1.63	1.56; 1.92
	Bus	1.14	0.96; 1.35	1.68; 2.07	1.25; 1.27	0.82; 1.18	1.56; 1.92
	Metro	1.14	0.16; 0.37	0.83; 1.04	0.51; 0.53	0.10; 0.28	0.73; 0.92
Off-peak hours							
	Car	-	1.07; 1.4	1.40; 1.64	-	1.07; 1.40	1.31; 1.63
	Bus	1.7	0.66; 1.00	0.96; 1.74	1.76; 1.80	0.48; 0.77	1.23; 1.53
	Metro	1.7	0.15; 0.39	1.31; 1.21	1.27; 1.31	0.00; 0.19	0.74; 0.94

5. Optimal and zero transit fares with constant car taxes in Brussels

It may be the case that an urban authority controls transit prices and service levels, while car taxes are set by an authority on a higher level. Also, it can be argued that reducing public transport prices is politically feasible, whereas implementing the optimal price structure is not. This could explain current policy in Belgium, where in recent years public transport is being provided at zero fares for an ever increasing number of users. It is then relevant to ask how public transport fares should be set when car taxes are fixed at the reference level. We do the exercise for Brussels, assuming that the urban authority gives an equal welfare weight to all transport users in the urban area. When transport tax revenues receive a premium of 6.6%, the resulting welfare improvements are as in Table 6.

Table 6 Percent welfare gains with respect to reference situation, positive tax revenue weight*

	Brussels	
	Optimal transit prices	Zero transit prices
No econ. of density	0.13	0.0
With econ. of density	0.20	0.02

* A zero weight to tax revenues leads to lower welfare gains.

The exclusive but optimal use of transit instruments permits a limited welfare gain. Up to 7% of the welfare gain from first best pricing can be reached, through the combined effect of fares and waiting time reductions. The car tax restriction has drastic effects on optimal transit fares: in off-peak hours fares are doubled with respect to the reference situation because the reference subsidies are not justified on efficiency grounds, while in peak-hours the fare is reduced to zero (nearly zero in some settings). The transit fare is used as much as possible as an indirect way to reduce peak period congestion. The peak period public transport share increases from 33% to 36%, which is less than under first-best pricing (43%). The off-peak share remains at 20%, in contrast to first-best, where a small decrease is found for the off-peak share of public transport.

Setting zero fares in both peak and off-peak hours reduces the welfare gain to zero or nearly zero.[17] This policy leads to a 2.1% increase of daily demand for passenger-kilometres, following from a 4% increase during peak hours and a 1% decrease in off-peak hours. We find, remarkably, a shift towards peak period transport despite the price decrease in the off-peak hours. This shift follows from substitution of off-peak car transport (-4.2%) to off-peak and especially peak period public transport (+12.8% and +17.5% respectively). During the peak period, 36% of all passenger-kilometres are by public transport (33% in the reference situation). The off-peak public transport share is 23% (instead of 20% in the reference equilibrium and 16% under first-best pricing).

Introducing zero fares presumably is attractive from an electoral point of view, and is not necessarily welfare reducing. However, other second-best policies may be feasible as well, e.g. reducing access to unpaid parking, and may allow more substantial welfare gains.

6. Optimal pricing and the public transport budget in Brussels

While it is in general preferable to value revenue requirements at the economy-wide cost of public funds, the budgetary situation of the operator may nevertheless be a point of policy interest.[18] Table 7 reports the operators' daily receipts, expenditures and revenue requirements for a number of the Brussels scenarios. It is assumed that the operator receives all fares, i.e. inclusive of external cost and revenue raising charges. The fixed costs of transit supply are not included in the table. They are equal to 0.373 million Euro per day for the Brussels case.

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[17] The gains from free transit are entirely due to the indirect effects on congestion levels. The scale and the characteristics of the Brussels case study rule out large substitution from non-motorised transport to transit. Such substitution could reduce the social benefits from free transit provision.

[18] For all scenarios in Table 7, it is assumed that tax revenues are used to decrease existing taxes, implying that surpluses should not remain within the public transport sector.

Clearly, the public transport sector is more than self-financing when first-best pricing conditions prevail, even after inclusion of the fixed costs. When economies of density in the form of waiting time reductions are present, the receipts decrease and the expenditures increase, but the balance remains positive because of the charges for congestion and other externalities.

Table 7 Public transport budget for Brussels scenarios without economies of density and with endogenous waiting times (million EURO/day)

Pricing conditions	Tax revenue premium	Economies of density	Receipts (farebox revenue)	Expenditures (excluding fixed costs)	Balance
Reference			0.311	0.321	-0.009
First best	0	No	1.056	0.312	0.745
		Yes	0.797	0.352	0.445
First best	6.6%	No	2.326	0.281	2.045
		Yes	2.023	0.315	1.708
Second best (fixed car taxes)	0	No	0.152	0.322	-0.170
		Yes	0.125	0.329	-0.204
Second best (fixed car taxes)	6.6%	No	0.176	0.319	-0.143
		Yes	0.135	0.326	-0.191
Free transit (fixed car taxes)	6.6%	No	0	0.357	-0.357
		Yes	0	0.363	-0.363

When car prices cannot be changed and public transport prices are optimised, the public transport sector shows a substantial deficit. The deficit becomes larger when service frequencies are optimised. Setting zero transport prices in all public transport markets makes for a substantially larger deficit than in the previous case. Finally, the fact that the budget is nearly balanced in the reference situation may reflect regulatory conditions, if these require the operator to break even on variable costs.

7. Comparison to earlier studies

We compare our results to those of three earlier analyses, which are particularly relevant here as they determine optimal price and service characteristics for multimodal urban transport systems, taking account of externalities and economies of density. Neither of the studies attaches a positive premium to transport tax revenues, so that the relevant comparison is with the results that we obtain with the zero tax revenue premium.

First, Viton (1983) combines a stylised spatial model of urban transport costs with a random utility demand model, to analyse the impact of efficient pricing. Total peak trip demand is fixed, and the cross-price elasticity with off-peak demand is zero. In the off-peak periods, the modal split is exogenously given. An additional public transport passenger, at a given supply of vehicle-kilometres, does not cause an increase in external costs. In case studies for the Bay Area and for Pittsburgh, he finds that optimal transit fares are well below current fares (and are virtually zero), that waiting times decrease and that the optimal modal share of transit is much larger than at present, up to 100% in some cases. According to Viton, the results are explained by the change in the relative generalised prices of car and bus trips. Car prices increase because of the tolls, and generalised bus prices decrease because of lower fares and higher service frequencies and a denser bus network. Clearly, our model produces less pronounced increases in transit's modal share: it increases by 10%-point during peak hours. The combined effects of our assumptions that peak demand is elastic and that an extra bus passenger does contribute to congestion and to other externalities, go some way in explaining this difference. Presumably the cross-price elasticities across modes are higher in Viton's model than in ours, as well.

Second, De Borger and Wouters (1998) use a model of the Belgian transport market, with an explicit representation of the relation between transit supply in vehicle-kilometres, the number of vehicles used, and occupancy rates. Their applied model contains a less detailed set of transport markets than ours, and no marginal cost of public funds. The authors find that (first-best) welfare maximisation requires strong transit price decreases and supply increases in comparison to the reference situation. In an application for Belgium, transit prices decrease by 61% (peak) to 84% (off-peak). Supply increases by 13% (peak) and 54% (off-peak). The reasons for these findings are the returns to scale in transit (which we neglect), the low off-peak marginal costs per passenger-kilometre, and the more limited severity of congestion during peak hours. The increased attractiveness of transit also implies that optimal car prices increase less than in a situation without returns to scale. The modal share of buses increases from 3% in the reference situation to 7% in the first-best equilibrium, an order of magnitude comparable to our findings (especially taking into account that their case study is for Belgium, while ours are on an urban level).

Third, Winston and Shirley (1998) look for an efficient urban transport system by setting prices equal to marginal social costs for cars, in a set of American cities. As in our model, the central scenario assumes that occupancy rates in public transport are fixed. Congestion tolls are introduced for cars, but not for buses. An alternative scenario endogenises occupancy rates and waiting times. When occupancy rates are constant, welfare improves. Consumer surplus in transport markets is reduced, but this is more than compensated by the reduced public transport deficits and the increased transport tax revenue. Transit subsidies are virtually eliminated, and the optimal modal share of transit is even lower than the reference share. Benefits are higher when economies of density are taken into account, because service frequency is reduced and this improves the sector's budget balance. In the optimal situation where tolls are introduced, frequencies optimised, and transit costs reduced by 15% because of reduced X-inefficiency, bus fares would increase by a factor of four, and frequency is cut by more than two-thirds in comparison to the reference situation. Buses' modal share is reduced from 5% to 1%.

These results are very different from the ones that we obtain for peak periods in both cities (increased modal shares for public transport and lower waiting times), although the orders of magnitude of fare increases are similar. Note however that our fare increases follow from the congestion tolling component of the optimal fare, which is absent from Winston and Shirley's model. We obtain similar directions of change for buses in offpeak hours, when congestion is relatively less important: fares and waiting times increase, and the modal share decreases in Brussels). This suggests that Winston and Shirley's results on public transport are mainly driven by the reduction of excessively large initial subsidies (as is the case in the offpeak period in Brussels in our model), which are partly explained by the very low average occupancy rates: the average bus load factor is 14.3%, the average fare is 13 cents per mile, and the average marginal cost per mile is 65 cents (p. 50). In the two cities that we consider, bus occupancy rates are higher (even in offpeak periods), and the per unit distance subsidy is smaller (except in the offpeak in Brussels bus market). All of this corroborates the interpretation that, given the preferences, the urban spatial structure and high fuel prices, public transport is more of a viable option in Brussels and in London than it is in the US cities analyzed by Winston and Shirley (1998).[19]

8. Concluding remarks

Calculations of optimal urban transport prices for Brussels and London show that taking account of economies of density in public transport and of tax revenue premiums increases the welfare gains. Congestion costs and shadow values of transport tax revenues dominate the optimal price structure. The market share of public transport modes is much higher in the optimised equilibrium than it is in the reference case.

Several caveats should be mentioned. No account was taken of boarding, alighting and crowding externalities in public transport. They are likely to increase optimal fares. More in general, the supply of transit could be modelled in more detail. Ideally a spatial model should be used, which would allow taking account of bus route characteristics and of endogenous determination of bus stops. Finally, we used efficiency as a social welfare criterion. When public transport is more intensively used by low income groups, it may be

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[19] Brueckner (2003) reports that fares cover approximately 50% of operating costs in European cities, against 38% for the U.S.

justified to price it below marginal social costs for reasons of equity (Mayeres and Proost, 2001).

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