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OPTIMAL PRICING FOR URBAN ROAD TRANSPORT EXTERNALITIES

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Abstract

A partial equilibrium model for the urban transport market is described. The urban transport market is represented as a set of interrelated transport submarkets, one per type of mode or vehicle and period. This allows to represent in detail the different external costs associated with the use of different modes: congestion, accidents, air pollution and noise. The model allows to find second best optima that combine optimally given pricing and environmental regulation instruments. The model is demonstrated for Brussels. For this city the welfare effects of alternative sets of instruments are compared.

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I. INTRODUCTION

Road transport generates different types of external costs. These include air pollution, noise and external costs more specific to urban transport, such as congestion and accident externalities. Those problems are most often dealt with by piecemeal or indirect policies. In Europe, the overall level of car traffic is limited through high excise taxes on motor fuels[2], parking policies and subsidies to public transport. Air pollution problems are tackled mainly by emission standards for cars and by differentiated excises on fuels (leaded versus unleaded gasoline). There is a need for integration of these policy actions in a consistent framework because they all contribute to the same objectives. One can indeed reduce air pollution through emission standards on cars, but also via subsidies to public transport or higher taxes on car use. We present a partial equilibrium model of urban transport markets, in which the different external cost aspects are integrated, as a tool for integrated policy assessment.

In the TRENEN-URBAN model, transport activities in an urban area are represented as a set of interrelated transport markets. A market corresponds to the use of a particular transport mode (e.g. small petrol car) with a given occupancy rate (pooled or not) in a particular time interval (peak or off-peak) in a homogenous city. Demand on each market is a function of the generalised costs on all markets. The generalised cost of trips consists of resource costs, time costs and different types of taxes. The markets interact through changes in the generalised costs that are either exogenous (tax changes) or endogenous: time costs depend on the total volume of transport on the network. This detailed representation of the transport market allows to represent explicitly congestion, air pollution, noise and accident externalities.

A market equilibrium is reached through maximisation of a welfare function under a set of constraints on the policy instruments. Relaxing the policy constraints allows to construct counterfactual equilibria and to assess the relative merits of different pricing and regulatory policy instruments.

This paper extends a previous urban transport model (DE BORGER, MAYERES, PROOST, WOUTERS (1996)) that focused only on optimal pricing policies, did not use an

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[2] In general fuel taxes are levied for government budget considerations rather than for external cost internalisation.

explicit welfare criterion and had a strongly simplified demand and supply structure. The principal contribution of this paper is the explicit computation of optimal taxes and regulations that internalise different types of externalities in a second best framework. Previous contributions to the optimal transport pricing problem in a second best framework include the seminal papers by GLAISTER & LEWIS (1978) and SMALL (1983). These papers focused on congestion externalities only and were limited to two modes.

In terms of degree of detail, the TRENEN-URBAN model is an intermediate solution between a general equilibrium model and a typical transport model. In a general equilibrium model, transport is just one of the goods considered and optimal direct and indirect taxes can be computed in a second best framework à la ATKINSON and STIGLITZ (1980). In a typical transport model[3], the transport operations of the different modes are represented in detail on a network and the main goal is the correct simulation of the flows on the network. Our approach drops, on the one hand, the explicit network representation of the transport flows by assuming a homogeneous zone, while retaining the detailed representation of transport volumes by mode. The relevant information of the network model is summarised in an aggregate flow-speed relationship. On the other hand, optimal taxes are computed only for transport markets by assuming separability with the non-transport goods and using a marginal cost of public funds approach to trade-off the welfare cost of raising taxes in the transport sector versus other sectors. The marginal cost of public funds is a parameter which can be supplied by a general equilibrium model.

Section 2 is on the theoretical structure of the model. Section 3 discusses the model implementation and the estimation of the different external costs of transport. The model is used for comparative static exercises on the expected transport equilibrium in Brussels for the year 2005. In section 4 we assess the relative merits of different policy instruments (electronic road pricing, improved parking charges, cordon pricing, optimised public transport prices and emission regulations for cars). Section 5 concludes.

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[3] See Small (1992) for an overview.

II. MATHEMATICAL FORMULATION

This section develops a simplified version of the partial equilibrium model that we use for simulating policy optimised equilibria.

Assume N identical individuals and i=1,..,I different passenger transport demand categories (use of bus, small car, large car, etc.). Each mode can be produced by j=1,..,J supply technologies (e.g. for i= small car we could have small car without or with catalytic converter (j=1 or 2). Similarly there are f=1,..,F different freight transport demand categories, satisfied by J different supply categories. Individual passenger transport demand for a certain type i of transport equals x_i and is satisfied by a total supply of J different car technologies z_{ij}. Freight demand using mode f is denoted x_f and can be satisfied by j technologies (z_{fj})[4]. C (element c) denotes the set of consumer goods : C={q_o, q_i; I=1,…,I}.

The policy maker maximises the sum of consumers' surplus of passenger and freight transport users, producers' surplus of the suppliers of transport, and the tax revenue weighted by the marginal cost of public funds, minus external costs. Government selects taxes (by setting the consumer and producer prices) for all transport goods and determines, through regulation, the types of transport technologies to be used to satisfy demand for each mode.

This is the traditional formulation for a regulatory problem with perfect information for the policy maker: the policy maker knows the demand functions and the marginal costs of the different supply options, and fixes the equilibrium by setting consumer prices and regulating supply. Tax revenues are returned to the consumers in a lump sum way. Tax revenues receive, via the marginal cost of public funds parameter, a larger weight than consumer and producer welfare because it is costly to collect tax revenue. Using a marginal cost of public funds approach is preferable to the use of an absolute budget constraint for the public transport authority because the implicit marginal cost of this constraint is unknown beforehand and can diverge strongly from the cost of collecting public funds on other markets (see LAFFONT and TIROLE (1994)).

This is a partial equilibrium approach in the sense that the feedback on non-transport markets are neglected. More specifically, prices on other markets, including the price of

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[4] The notation of indices is as follows: i and k are used to denote the different passenger transport modes, f and g denote the different freight transport modes and l denotes both passenger and freight transport modes. The type of technology is indexed with j.

inputs for transport, are fixed, tax revenue is returned in a lump sum way, and the valuation of externalities only depends on changes in the transport market.

1. Representation of demand and supply

Demand functions are defined as a function of the generalised price of transport: the cost of transport consists of a money cost (the public transport fare or the expenditures for the use of a car, q_i) and a time cost (the time necessary for the trip, t_i, times the value of time, ρ_i). Time costs may depend on the mode of transport (passenger or freight, car or public transport) and on the discomfort of the users (a minute lost in the morning peak has a higher subjective value than a minute lost during a shopping trip in the afternoon).

The generalised price for a passenger km with modus i is thus defined as:

$$generalized\ price_i = q_i + \rho_i t_i \tag{1}$$

The use of generalised prices is a shortcut for a more elaborate model with endogenous values of time. This is justified as long as values of time do not change between two equilibria. The generalised price plays an important role in the model: travel times are endogenous, as they depend on the level of congestion of the transport mode used.

Consumer surpluses are no longer unique in the case of interdependent demand functions for transport. Therefore, we use the indirect utility function V(income, $q_i + \rho_i t_i$,..), function of generalised prices and income, divided by the marginal utility of income in the reference equilibrium ($\mu(0)$) as welfare measure for the consumers of transport. The consumer surplus of freight transport demand is given by the cost function of a unique producer. The indirect utility function and the cost function implicitly define demand for transport.

The supply side representation is simple. The producer price per vehicle km with mode i is p_i. The marginal resource costs of supplying vehicle km with mode i and technology type j are taken constant and equal rc_{ij}.

2. Representation of congestion and the other externalities

For the representation of congestion we opt for the reduced form approach of flow–speed relationship, rather than for the more structural bottleneck model (see ARNOTT, DE PALMA, LINDSEY (1993)). The structural model allows a more detailed treatment of schedule delay costs. We focus on optimal pricing of different modes. See SMALL, CHU (1997) for a comparison of both approaches.

We assume that some transport modes share a common infrastructure of fixed capacity. The unit time t_i for a passenger km using mode i will depend on the total traffic volume sharing the road network. With:

- set S_i denoting the group of (passenger and freight transport) modes that use the same infrastructure (e.g. cars, trucks and public busses in the peak period),
- m_i the contribution of mode i to the overall congestion (e.g. a bus with 40 people adds per person less to congestion than a car with 1 person),

the general form of the congestion function is[5]:

$$t_i = T_i \left(\sum_{l \neq f \varepsilon S_i} m_l \, N \, x_l + \sum_{f \varepsilon S_i} m_f \, x_f \right) \tag{2}$$

Marginal external costs ec_{ij} other than congestion can be a function of any of the variables of the model. For simplicity they are taken as constant per vehicle km. These external costs depend on technology used (e.g. the polluting emissions of a car depend on the pollution abatement equipment j).

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[5] The same function can be written for the unit time t_f for a freight km using mode f:

$$t_f = T_f \left(\sum_{l \neq f \varepsilon S_f} m_l \, N \, x_l + \sum_{g \varepsilon S_f} m_g \, x_g \right)$$

3. Computation of the market equilibrium

We compute a market equilibrium by maximisation of the following welfare function:

$$MAX \frac{N}{\mu_r} V \left[q_o q_i + \rho_i t_i ; (i = 1, \ldots, I), Y + \frac{1}{N} \sum_{l,i} \left(p_l - rc_{li} \right) z_{li} + \frac{1}{N} \sum_{f} \left(q_f - p_f \right) x_f + \sum_{i} \left(q_i - p_i \right) x_i \right]$$
$$- C\left(q_f + \rho_f \ t_f ; f = 1, \ldots, F \right) + \lambda \sum_{i} \left(q_i - p_i \right) N \ x_I - \sum_{l,i} \left(ec_{li} \ z_{li} \right) \tag{3}$$

The first term measures utility as a function of generalised prices and income. Income consists of exogenous income (Y), profits from the transport supply industry and returned tax revenue from freight and passenger transport. Utility is converted into income terms by dividing it by the marginal utility of income (μ_r) in a reference situation. Prices of non-transport goods q_0 remain fixed. The second term measures the producer surplus of freight transport users. The third term measures the shadow value of public funds minus one (λ). No extra value was attributed to the tax revenue raised on freight demand because in general production efficiency is desirable (DIAMOND and MIRRLEES (1971)). The last term measures the total external cost damage excluding the congestion cost. The external congestion cost is implicitly represented in transport time costs which are included in the generalised prices.

The objective function is maximised with respect to p_i, q_i and z_{ij} , subject to the following constraints:

$$\sum_{j} z_{ij} \ \geq \ N x_i \ \ \forall i \tag{4}$$

$$\sum_{j} z_{fj} \ \geq \ x_f \ \ \forall f \tag{5}$$

$$p_l \ \geq \ rc_{lj} \ \ \forall l, j \tag{6}$$

In addition we require that all variables take positive values. The first two constraints state that demand has to be satisfied by the sum of the technologies supplied[6]. The third constraint states that producer prices are larger than the marginal resource costs, which is

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[6] The supply of transport has to be corrected for the occupancy rate in order to match the demand of passenger km.

justified by incentive compatibility constraints for producers. Subsidies to private or public transport are represented by a producer price larger than the consumer price.

We assume that this objective function is well-behaved, that the maximum problem has a solution. A unique solution is not guaranteed[7]. We use Lagrange multipliers α_i, α_f for the first set of constraints and γ_{ij} for the second set of constraints, and look for an optimum with respect to the control variables q_i, q_f and $z_{i+f,j}$. This implies that the demand levels x are controlled indirectly via the consumer prices q so that all optima of the model are by construction consumer optima (passenger transport) or cost optima (freight transport). Taxes on consumer goods are implicitly determined by the difference between q and p. The optimum will satisfy the complementary slackness conditions associated to (4), (5) and (6) as well as the following first order Kuhn Tucker conditions for an interior optimum (x_{kqi} represents the derivative of x_k with respect to the consumer price of good i and μ stands for the marginal utility of income in the new equilibrium):

$$\begin{aligned} &- \mu \frac{N}{\mu(0)} x_i - N \frac{\mu}{\mu(0)} \sum_{l \neq f \varepsilon S_i} \rho_l x_l t_{lq_i} - \sum_{f \varepsilon S_i} \rho_f x_f t_{fq_i} \\ &+ \frac{\mu}{\mu(0)} N x_i + N \frac{\mu}{\mu(0)} \sum_k (q_k - p_k) x_{kq_i} \\ &+ \lambda N x_i + \lambda \sum_k (q_k - p_k) N x_{kq_i} + \sum_k \alpha_k N x_{kq_i} = 0 \end{aligned} \tag{7}$$

$$\begin{aligned} &- N \frac{\mu}{\mu(0)} \sum_{l \neq f \varepsilon S_i} \rho_l x_l t_{lq_f} - \sum_{f \varepsilon S_i} \rho_f x_f t_{fq_f} + \frac{\mu}{\mu(0)} \sum_g (q_g - p_g) x_{gf} \\ &+ \frac{\mu}{\mu(0)} x_f - x_f + \sum_g \alpha_g x_{g_f} = 0 \end{aligned} \tag{8}$$

$$\frac{\mu}{\mu(0)} \left(\sum_j z_{ij} - N x_i \right) - \lambda N x_i - \gamma_{ij} = 0 \tag{9}$$

$$\frac{\mu}{\mu(0)} \left(\sum_j z_{fj} - x_f \right) - \gamma_{fj} = 0 \tag{10}$$

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[7] Optimal tax problems can have local maxima (Diamond and Mirrlees (1971). In the model applications we experienced no problems as we always start from a feasible reference situation.

$$\frac{\mu}{\mu_0}(p_l - rc_{lj}) - ec_{lj} - \alpha_l = 0 \tag{11}$$

4. The maximum as a policy optimised market equilibrium

It can be shown that the solution to this maximisation problem corresponds to a market equilibrium where :

- government regulates the supply technologies to be used,
- producers maximise profits, taking prices as given,
- consumers select their preferred consumption bundle given the consumer prices, and
- government combines regulations and consumer taxes to maximise overall welfare.

Given the construction of the objective function, all solutions are optimum budget allocations or minimum cost allocations for given generalised prices. Assume provisionally that there is no excess supply at the optimum, because this would constitute a pure loss at least equal to the resource cost. This implies via the complementary slackness condition associated to (4) that $\alpha_i > 0$. For each final transport good k at least one technology g is used such that $z_{kh} > 0$. This implies through (11) that for whatever technologies g and h used in the optimum to satisfy demand k, we must have:

$$rc_{kl} + ec_{kl} = rc_{kn} + ec_{kn} \tag{12}$$

Consequently in each welfare optimum the sum of resource costs and external costs determines which technologies should be used. Hence, choice of technology does not depend on any other parameter (not on λ, in particular).

Because the producer price p_i is identical for g and h and because the producer only has to pay for resource costs, a cost minimising producer would not necessarily select the socially optimal technology. Therefore, we need to introduce the regulation of the type of technology to be used, as a policy instrument[8]. In the optimum and for normal values of $\lambda > 0$, producer prices will, for all technologies used, always be equal to the resource costs. To see why, assume that prices are higher than the resource costs. Then the government

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[8] In an alternative model set-up, not discussed here, the policy maker could replace the technology regulations by a tax on producers or on consumers in function of the type of technologies that are used. The choice between regulation, taxing externalities at the stage of producers or at the stage of consumers is not important in this model where the policy maker is perfectly informed and disposes on perfect policy instruments.

can increase its tax revenue at the expense of the lower valued producer surplus by keeping constant q but lowering p until it reaches the resource costs. We conclude that, in the selected optimum, producer prices equal the lowest marginal resource costs of the set of technologies allowed by the policy maker. This corresponds to the outcome of a perfectly competitive market with regulations on the type of transport technologies that can be used.

For the interpretation of the optimal tax rules it helps to restrict the analysis first to the case where demand for each transport good only depends on its own price. Using (7) and (11) we obtain for the optimal tax on passenger transport:

$$\left[t_k - \frac{tmcong_k + ec_k}{(1+\lambda\,\mu(0)/\mu)}\right]\frac{E_{kk}}{q_k} = -\frac{\lambda\,\mu(0)/\mu}{1+\lambda\,\mu(0)/\mu} \tag{13}$$

where tmcong$_k$ is the total marginal congestion cost of increasing the use of passenger transport mode k (T_{ii} and T_{ff} represent the derivative of unit transport time of respectively passenger and freight transport with respect to the total volume of transport and m_k the contribution of mode k to congestion):

$$tmcong_k = m_k\left[N\sum_{i\varepsilon S_k}\rho_i\ x_i\ T_{ii} + \frac{\mu}{\mu(0)}\sum_{f\varepsilon S_i}\rho_f\ x_f\ T_{ff}\right] \tag{14}$$

When there are no external effects, (13) becomes the familiar Ramsey expression where taxes are inversely proportional to the own price elasticity. The general level of taxes on consumer goods will increase when the shadow cost of public funds λ increases. The term $\mu(0)/\mu$ is an approximation term with a value close to 1.

Consider now the case with external costs. The external congestion cost of an increase of passenger transport of type k is defined in (14) and consists of the value of the time losses for all transport users (passengers and freight). In (13), taxes become Pigouvian taxes when $\lambda=0$.

When λ increases, the externality part of the optimal tax decreases below the pure Pigouvian component and the Ramsey component increases. Intuitively a higher λ means that the second role of the tax (to raise revenue) becomes more important and that therefore the policy maker can afford less tax differentiation aimed at environmental protection as this counteracts the revenue raising objective of the tax system. This trade-off has been studied by BOVENBERG and DE MOOIJ (1994) and BOVENBERG and GOULDER (1996) in a general equilibrium context. They pointed out that, in the absence of feedback’s from the externality on the consumption of taxed goods, a higher cost of public funds will in general imply lower rather than higher externality taxes. This contradicts the popular second dividend hypothesis where higher environmental taxes were meant to lower labour taxes.

This reasoning can be transplanted to our partial equilibrium model with two qualifications. First ,we deal with congestion and this is a type of externality that feeds back on the consumption of taxed goods. MAYERES and PROOST (1997) have shown that this requires a complex correction of the externality term so that only empirical studies can bring about conclusions on this point. Second, in a partial equilibrium approach, no account is taken of the use of the tax revenue and its ultimate effect on the cost of public funds. This procedure is only justified if the variations in tax revenues studied with the transport model can be considered as marginal.

When we consider the cross price effects between passenger transport goods, existing price distortions for complements and substitutes have to be taken into account. Cross price effects become very important when there are restrictions on the taxation of certain modes (e.g. car use in the peak period). In this case there are large distortions between the social cost and the price of that mode and this can require important deviations from social cost pricing for substitute modes (e.g. subsidies for public transport).
Restricting ourselves to the case without cross-price effects for optimal taxes on freight transport, (8) and (11) imply:

$$\left[t_f \; - \; tmcong_f \; - \mu(0)/\mu \; ec_{fj} \right] \frac{E_{ff}}{q_f} \; = \; (\mu(0)/\mu \; - \; 1) \qquad (15)$$

When the μ(0)/μ approximation is perfect, we have pure Pigouvian taxes that preserve production efficiency, as advocated by DIAMOND and MIRRLEES (1971). The difference between (15) and (13) lies in the λ: public revenue considerations are absent when setting indirect taxes to firms.

Optimality conditions (12), (13) and (15) will be driving all model results shown later. The basic model shown here can be extended in several ways. We will discuss briefly three additional features that have been introduced in the empirical model (sections 5, 6 and 7).

$$- N \; x_l \; \rho_l \; \frac{\delta \, t_l}{\delta\phi} \; = \; \frac{\delta \, RC_l}{\delta\phi} \qquad (16)$$

This means that the frequency of service should be increased up to the point where the marginal savings in waiting time for all users equal the marginal resource cost of improving the frequency of service. This is in line with a result by VITON (1983) who states that the public transport authority should select the quality of service so as to minimise the sum of waiting times and resource costs for the transit authority. In our case this result holds independently of the marginal cost of public funds λ because the money price of public transport is fully controlled by another policy variable. If the prices of the different modes can not be all controlled, all terms of equation (7) become relevant again and have to be added to equation (16). Choosing the quality of service of public transport then becomes an indirect instrument to lower the generalised cost of public transport and to make car users switch away from their undertaxed mode.

6. The marginal cost of public funds

In the welfare function, changes in tax revenue (including public transport deficits) are valued at the marginal cost of public funds minus 1 (λ) and tax revenue is returned in a lump sum way to the individual. This reduced form formulation for a partial equilibrium framework needs some more explanation.

One can consider the utility derived from the transport goods and the consumption good in the utility function in (3) as a composite consumption good CC. Assume further that the individual has no other sources of income than labour. Taxes are on labour and on consumption.

In the partial equilibrium model, we derive the optimal change in taxes on transport goods. A change in taxes on transport will change the aggregate tax on the composite consumption good and it is this revenue effect we want to value. It will depend on the way the extra tax revenue is used. If supply of public goods and transfer programs remain unchanged, then the extra tax revenue can be used to decrease labour taxes. If all individuals are identical, the decrease in labour tax will not generate any efficiency gain: real wages will remain unchanged because of the increase in the aggregate consumption tax. In this case, no welfare gain can be attributed to the increase of tax revenue raised on consumption activities and λ equals 0. Because the wage rate is absent in the model formulated in (3), the revenue effect is approximated by adding tax revenue to income.

The value of λ will be different if another use is made of the changes in the tax revenue from CC. Assume that there are other sources of income than labour, more specifically that a share κ of total income is non labour income. If all extra tax revenue is used to decrease labour taxes, the net tax wedge on wages will decrease and the welfare gain of this decrease will be equal to:

$$(MCPF_{labour} - 1)\,\mu\, dREV \tag{17}$$

where the marginal cost of public funds raised by a labour tax can be computed on the basis of a labour supply equation and where dREV stands for tax revenue collected from consumption and transport goods. The fundamental reason to have $\lambda>0$ is a shift of the tax burden from labour to non labour income.

One can imagine less efficient uses of the extra tax revenue and this will have an impact on the model formulation. If tax revenue is returned as a head subsidy, expression (17) becomes $(1-MCPF_{labour})(1-\kappa)dREV$, because the net tax wedge on labour has been increased. As the value attributed to extra tax revenue is now negative there is an incentive not to increase transport taxes too much.

7. Non identical individuals

The model can be reformulated with multiple types of individuals. Individuals can differ in the transport opportunities they have, in the income and prices they face and also in their preferences. The welfare function can be adapted using social welfare weights that are taken as constant in the optimisation of the transport prices. These welfare weights are defined as the relative social marginal utility of real income. All the elements of objective function (3) have to be allocated to individuals for this system to work: the distribution of the extra tax revenue, the distribution of the change in real profits, the distribution of the efficiency gains on the labour market and the distribution of the damage of external effects.

8. Constraints on policy instruments

Constraints on the use of policy instruments exist. In fact, only certain inputs to the use of transport means can be taxed (fuel, vehicle, tolls, etc.), rather than the actual use of the modes itself. This heavily restricts the pricing possibilities. The model can handle these constraints. When more constraints are introduced on the pricing instruments, the first order conditions become analytically more and more intractable so that only numerical simulations can bring definite answers.

9. The use of the model for comparative statics

The model is calibrated by plugging in observed or expected taxes and prices, quantities and regulations. This generates a reference market equilibrium.

Alternative market equilibria can be generated by changing the taxes or regulations. This is done by solving again the maximum problem (3) to (6), to which constraints on the values of tax parameters and the type of technologies are added. An infinity of market equilibria can be generated by the model in this simulation mode. Of particular interest are the best equilibria obtainable with a given set of tax and regulation instruments. These can be found by using the model in an optimisation mode, where the choice of the tax parameters is the solution to the maximum problem (3) to (6) with restrictions on the type (not the value) of policy instruments. In section 4 the model will explore in this way the performance of different sets of policy instruments.

III. OPERATIONALISING THE MODEL CONCEPTS

We discuss consecutively the representation of demand, supply, external costs, the congestion function and the marginal cost of public funds. The model application is for Brussels, a city of medium size with an extensive road and public transport network. The predicted transport situation in 2005 for unchanged policy conditions will serve as reference equilibrium. The applications discussed in section 4 do not include freight transport in the analysis.

1. Demand representation

Four groups of consumers are distinguished. First we distinguish between inhabitants and commuters. For each of these categories a further distinction is made between those who have access to free parking and those who do not.

Passenger transport demand is represented using a nested CES function (KELLER (1976)). The CES function is easy to calibrate and requires a minimum of behavioural information: prices and quantities in a reference equilibrium together with substitution elasticities at each level. Nested logit functions are in theory a superior way to represent transport demand, but they are more data intensive and can not easily be used for the computation of optimal taxes.

The specific nested CES utility function used contains seven nests. The elasticities of substitution are determined:

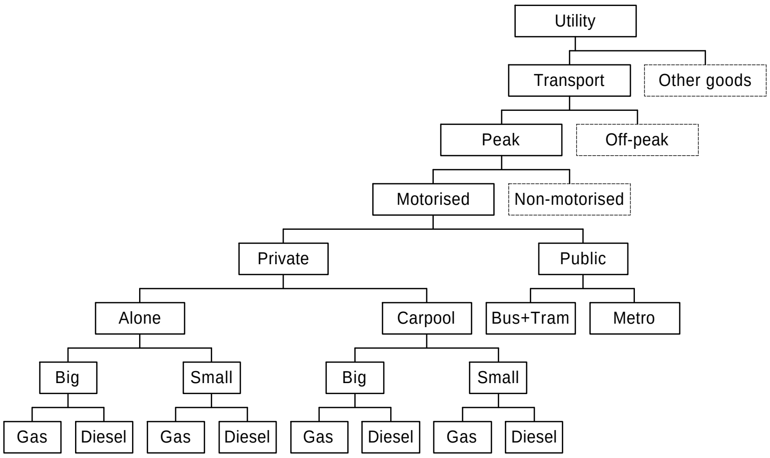
- assuming that the lower we go down the tree, the easier one can substitute between the alternatives,
- such that they yield price elasticities consistent with the literature.

This leads to the following values :

0. transport and non transport goods (0.6)
1. peak and off peak transport (0.8)
2. motorised and non motorised transport (walking, bicycle and motorcycles) (0.3)
3. public and private transport (1.05 in peak and 1.95 in off-peak)
4. solo or carpool for car (0.6 in peak and 1.6 in off peak)
4. metro or bus & tram for public transport (1.1 in peak and 1.65 in off peak)
5. small and large cars (1.5)
6. petrol and diesel cars (1.5)

The full structure is shown in Figure 1 in the form of a utility tree.

Figure 1: Utility tree for urban passenger transport in TRENEN II URBAN - Elaboration of peak-branch



In determining the order of the nests one should bear in mind the assumption of separability underlying the nested structure. All goods located on the same branch of a tree will react identically to a price change of a good on another branch of the tree.

Car pooling is considered as a separate mode because in this way the overall occupancy rate for cars becomes endogenous. The non-motorised modes are aggregated into one mode because we emphasise congestion and air pollution problems. Most of the branches have only two choices, but they can be extended to any number.

2. Supply representation

The supply part is kept very simple in this model. Its main function is to represent the resource costs of alternative transport modes. We distinguish between public and private transport.

A. Private transport modes

For private passenger transport modes, a distinction is made between large and small cars, between diesel and petrol cars and between pooled and non-pooled cars. Resource costs are taken as constant per vehicle kilometre for each of these categories. This implies that the costs of ownership and of use of cars are not addressed separately. This is acceptable a static implementation of a model that represents a long run adjustment.

For petrol cars two technological options are distinguished: standard technology which includes a normal 3 way catalytic converter and improved technology containing a pre-heated 3 way catalytic converter. The latter is more efficient in reducing harmful emissions in urban areas. For diesel cars there are also two possibilities. The improved technology adds, a.o., a De-NOx to the standard technology.

For private transport modes, six inputs are required to produce a carkm. There is no substitution possible between these inputs. To obtain one km in period X by individual of type Y with cartype Z, a fixed amount of fuel and parking time is needed. The other costs are vehicle depreciation costs, insurance costs, and maintenance costs. When the different types of taxes and the time costs are added to the resource costs, one obtains generalised prices.

B. Public transport modes

We consider two types of public transport, busses and trams, and underground. Busses and trams are defined as one mode because they are perceived by users as transport modes with the same quality. Busses and trams also (largely) use the same network and contribute to overall road congestion. Both public transport modes are represented by a linear cost function that contains a fixed cost and a proportional variable cost which differs by period: vehicle investment costs are fully allocated to the peak period.

For the representation of economies of density in public transport, we adapt MOHRINGs' (1972) framework. If all modes can be priced optimally, welfare maximisation requires that the choice of the optimal bus frequency is done such that the sum of bus company costs and waiting times is minimal, taking public transport demand as given. Let total cost per trip (χ), equal the sum of vehicle operating costs (C), walking time, waiting time and in vehicle time. Then optimal frequency per hour is given by

$$\phi^* = \left(\frac{\alpha V \beta\ D}{C} \right)^{(1/2)} \tag{18}$$

where
ϕ frequency per hour
D demand for trips per hour
α factor for obtaining value of waiting and walking time from value of in vehicle time
V value of in vehicle time in ECU/h

β factor for obtaining waiting time from headway

The resulting rule links frequency, hence waiting time, to public transport demand. It is introduced in the numerical model.

3. The congestion function

The model represents the city as a hypothetical one link system with homogenous congestion conditions. The congestion function is exponential. The precise functional form is based on extensive tests with detailed urban network models (KIRWAN, O'MAHONY, O'SULLIVAN (1994)).

4. External costs

The methodology used in the estimation and valuation of the external costs of congestion, noise and accidents is described in detail in MAYERES, OCHELEN, PROOST (1996). Emission factors and valuations for air pollution are based on ExternE data (BICKELL et al. (1997)). We briefly discuss the valuation assumptions and the orders of magnitude, in the reference situation with unchanged policy of the external congestion, air pollution, noise and accident costs.

Table 1: The marginal external costs of transport in Brussels, 2005, ECU/vkm

	Congestion	Air pollution	Noise	Accidents	Total
peak, small petrol car	1.796	0.004	0.002	0.033	1.835
peak, small diesel car	1.796	0.03	0.002	0.033	1.861
off-peak, small petrol car	0.003	0.004	0.007	0.033	0.047
peak, bus and tram	3.595	0.025	0.02	0.024	3.664
off-peak, bus and tram	0.005	0.025	0.07	0.024	0.124
peak, underground	0	0.005	0	0.003	0.008
off-peak, underground	0	0.005	0	0.003	0.008

Source : Mayeres, Ochelen, Proost (1996), Bickell et al. (1997)

The level of marginal external congestion cost in the reference period 2005 is shown in the first column of table 1. In the peak period congestion is the dominant external cost. The large value is explained by the steepness of the congestion function. In the case study, external congestion costs can be reduced by car pooling, by substitution to public transport or by lowering the volume of transport.

Marginal external air pollution costs per vehicle km have been assumed constant in this paper. In the case study, the total air pollution costs can be reduced by choosing a cleaner car, a smaller car, a different, cleaner, transport mode or by reducing the volume of transport. More fuel-efficient cars were not introduced as a specific option.

The external costs of noise contain the subjective discomfort of all inhabitants of a city caused by vehicle noise. Using a detailed study of the noise production by traffic in Brussels we derived an expression for the average noise level over a given period as a function of the volume and the composition of the traffic flow. This allows the computation of the marginal noise contribution of an extra vehicle km. The basis for the monetary valuation is the loss of value of houses in more noisy areas. The marginal external cost of noise is higher in the off peak than in the peak. No possibility was foreseen to reduce the noise level of cars or busses by technical means.

In the accident costs one takes into account three types of costs: the willingness to pay of the victim to avoid an accident, the willingness to pay of the victims’ family and friends to avoid an accident, and the direct economic costs of an accident (output loss for society, medical costs). The total social accident cost of adding an additional vehicle consists of two elements: the total accident costs for the occupants of the extra vehicle plus the increase in accident costs for all other road users, due to the increased accident risk. The first category of social costs is internalised to a large extent by insurance premiums and because drivers take their own utility loss due to accident risk into account when deciding to make a trip. The only social costs of this category that are not internalised, are the costs to society which are not recovered from insurance companies (ambulance costs, some medical costs etc.). Their magnitude depends on the insurance contracts. In Belgium, only costs related to the driver (not the passenger) are therefore included in the marginal external accident cost.

The second category, increased accident costs for other road users, is not internalised at all. This external cost is zero when adding more cars does not affect the average accident risk. We accepted this assumption on the basis of recent empirical evidence by (DICKERSON et.al., 1998). The external costs are computed on the basis of observed accident risk, taking into account three different types of accidents (fatal, serious injury and light injury).

In this approach, total external accident costs can only be reduced by substituting between modes (from car and bus to metro) or by affecting the total volume of traffic. One could imagine a more complex setting where the accident costs are linked to car design and drivers' behaviour. The total accident risks can then be reduced by linking insurance fees and taxes to these two elements. Of course also other elements linked to infrastructure are of importance, but they are kept fixed in this study.

5. The marginal cost of public funds

For the exercises in this paper it was assumed that all changes in indirect tax revenue are used to decrease labour taxes. Using the survey on marginal costs of public funds by SNOW and WARREN (1996), on marginal and effective tax rates from OECD (1996), and on labour supply elasticities from HANSSON and STUART (1985), a value of 1.2 was calculated for the marginal cost of public funds in Belgium. Since the share of labour income in total income equals 70% approximately (κ=0.3), the value of λ used in the applications is 0.066. This is the extra value given to a transfer from consumer surplus to tax revenue. This value is positive because by assumption any increase in the indirect tax revenues is used to shift taxes away from labour taxes by taxing also the non-labour owners.

6. The reference equilibrium in Brussel, 2005

The Brussels region has 0.95 million inhabitants and 0.65 million commuters. For both categories, it was assumed that 30% pay for parking in the reference situation (figure taken from HALCROW FOX (1996)). The peak period is 5 hours long (morning and evening peak), the off-peak is spread over 17 hours. The reference equilibrium is obtained by calibrating the model to the projected transport flows and prices in 2005, using the behavioural information contained in the elasticities of substitution.

The reference situation is described in table 2. The money price is the sum of resource costs and taxes. The generalised cost equals the money price plus time costs. Costs and prices are expressed per passenger km, using an occupancy rate of 1 for solo driving and 2.5 for carpooling in private transport, and 40 passengers per vehicle in peak hours versus 9 in off-peak hours, in public transport.

Table 2: Characterisation of the Reference Situation

Prices and costs (ECU/pkm)	Resource cost	Tax	Money price	Marginal external cost (per vkm)	Generalised price
Peak					
car, solo, small, petrol, free parking					
inhabitants	0.361	0.089	0.280	1.834	0.614
commuters	0.261	0.089	0.280	1.834	0.614
car, solo, small, petrol, paid parking					
inhabitants	0.361	0.089	0.450	1.834	0.784
commuters	0.261	0.089	0.350	1.834	0.684
car, solo, small, diesel, free parking					
inhabitants	0.326	0.083	0.271	1.863	0.547
bust/tram (inhabitants)	0.080	0.039	0.12	0.092	0.587
Off-peak					
car, solo, small, petrol, free parking					
inhabitants	0.359	0.083	0.271	0.047	0.419
bus/tram (inhabitants)	0.271	-0.151	0.12	0.014	0.521
Volume and composition of traffic	mio pkm	Share (%)	% carpool	Speed (km/h)	
Peak, private	3.846	41.6	29.6	23.1	
Peak, public	1.839	19.9		20.6	
Off-peak, private	2.839	30.7	25.4	49.7	
Off-peak, public	0.727	7.9		44.2	
Tax revenue (mio ECU/day)	0.508				
Private	-0.010				
Public					
Non-congestion External costs (mio ECU/day)	0.432				

In table 2 a distinction is made between individuals paying for parking and those having access to free parking. When shops or employers provide free parking, this reduces the tax base, so part of the resource cost of parking is in fact subsidised by the tax payer and part is borne directly by the parking firm whose losses are shared by the total population (cfr. net household income expression in (3)). For commuters the parking costs are spread over a longer trip so their total resource cost per trip (including parking) is smaller.

From a pure efficiency point of view, there are two fundamental problems in the reference situation. First there are drivers who do not pay the full resource costs of car use because they receive parking space for free. Parking costs account for 50% or more of the total resource costs of a carkm. As trip distances of commuters are larger on average, parking inefficiencies are smaller on a per kilometre basis for them. The parking inefficiency holds for the peak as well as for the off peak period. Secondly, there are large important external costs that are not corrected by the existing tax structure. Comparing the tax column with the marginal external cost column one finds large discrepancies in the peak for all modes. This is less the case in the off peak period. In this period taxes may be higher than marginal external costs for those who pay for parking. Public transport has a positive marginal external cost but is subsidised in the off-peak.. By subsidised we mean that the marginal resource cost is not covered, the fixed cost is covered by a lumpsum subsidy from the tax payer.

IV. ALTERNATIVE PRICING SOLUTIONS

1. Overview of scenarios

A wide variety of policy measures can be used to address the inefficiencies present in the reference situation. The origin of the inefficiencies is in the imperfect correspondence between marginal external costs and taxes. We first discuss the so called full optimum solution, in which all decision variables are optimised without any major constraint on the instruments. By imposing different series of constraints, we obtain second best solutions. We have chosen to present 4 policy alternatives where each time only one instrument is added to the reference equilibrium in an optimal way. The policy instruments are: optimal public transport prices, cordon pricing, regulated use of cleaner cars and a parking policy. Of course optimal policies will always contain a mix of instruments. The advantage of examining single policy alternatives is the transparency of the results.

Questions not addressed in the exercises presented here, but which the model is capable of handling, concern, amongst others, the dependence of results on revenue use (value of marginal cost of public funds[9] and types of revenue redistribution), the sensitivity to parameter values (congestion function, elasticities of substitution[10]), the extension of the model to allow for consumer choice of different sets of technologies[11], and distributional issues.

We describe the counterfactual equilibria which are compared in this paper.

- The full optimum (FO)

Full optimum private transport taxes differentiate between types of cars, occupancy rates, peak and off-peak driving, type of fuel and between inhabitants and commuters. Public transport fares can be fully differentiated as well. There is a constraint, however, in that we have imposed that the optimal taxes should be equal for drivers with and without access to free parking. Fully differentiated taxes can only be approximated by electronic road pricing

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[9] Experiments show that decreasing the value of λ will lead to lower taxes, but not to differences in the optimal tax structure.

[10] Different sets of values have been used to test the sensitivity of results. The set used here gives the best results in terms of accordance with observed price elasticities.

[11] This extension would be especially useful to study the effect of increased fuel prices. This may lead to overinvestment in clean technology, while the congestion problem remains largely unaffected.

systems. It is impossible for these systems to observe whether drivers pay for parking or not.

- Optimal public transport prices (OPT)

Here all private taxes remain unchanged and only public transport prices can be used as policy instruments. The optimal policy now differs from the policy found in the full optimum. Peak public transport prices will be strongly subsidised in order to correct in a second best way for the underpriced peak car travel. This leads to a zero money price for peak period public transport trips. The same phenomenon, but in a less strong way, leads to a small decrease of public transport fares during off-peak hours, in comparison with the reference situation.

- Cordon pricing (CP)

All prices remain unchanged for inhabitants of the Brussels region. Commuters will pass a cordon, i.e. a toll ring around the region, when entering the region. The toll levied at the cordon is differentiated optimally between peak and off-peak hours. There is no additional differentiation according to car type, etc. Public transport fares are at the reference levels. With this instrument, only part of the travellers face an improved pricing system. There are adverse effects : since commuters will travel less, inhabitants can travel at lower time costs and will hence increase their demand.

- Parking charges (PC)

In this scenario all consumers pay for the resource cost of parking. This implies a price increase for drivers who previously had free access to parking. This instrument shows what the merits are of bringing prices in line with resource costs for all consumers, without further action to correct for external costs. Given the importance of the inefficiencies in parking charges in Brussels in the reference situation, the relative welfare gain from this (supposedly) simple instrument is substantial.

- Regulated use of clean cars (SCC)

The only policy instrument here is to impose use of clean cars. It is assumed that consumers bear the resource cost increase caused by use of more expensive emission reduction technology. Data on resource costs and on benefits in terms of emission reductions are derived from the EU Auto Oil Programme (EC (1995)).

2. The full optimum

Full optimal pricing corrects the two inefficiencies of the reference situation. First, all drivers pay for the resource cost of parking at the city centre destination. Second, the marginal external cost is charged in all transport markets. In addition, account is taken of the impact of changes in transport tax revenue, through the marginal cost of public funds. Table 3 presents results.

We compare with the inefficient reference equilibrium of table 2. We want to emphasise three characteristics of the optimal pricing results.

A first characteristic is that marginal external costs in the optimal pricing equilibrium are less than one fourth of those in the reference equilibrium. This means that observed marginal external costs can be bad guides for computing optimal taxes. This can be seen in tables 2 and 3 by comparing the marginal external cost for the category car, solo, small petrol, paid parking in the peak (3 rd line) where marginal external costs drop from 1.834 ECU per vkm to 0.407.

A second characteristic is that optimal taxes in the transport sector are not necessarily equal to marginal external costs : they tend to be rather larger. The reason lies in the existence of distortions in the rest of the economy. In this application we have given a higher value to increases in transport sector tax revenue because of our assumption of recycling via labour taxes. The differences between taxes and marginal external costs are an application of Ramsey optimal tax rules.

A third characteristic is that optimal public transport prices also contain taxes to correct for their marginal external costs and to raise revenue. Optimal prices can still be below average resource costs as we assume a linear cost function. Generalised prices for public transport are lower in the optimum than in the reference. This is the result of increased speeds (lower congestion) and lower waiting times (economies of density), which compensate the higher taxes.

Table 3: Characterisation of full optimum

Prices and costs (ECU/pkm)	Resource cost	Tax	Money price	Marginal external cost (per vkm)	Generalised price
Peak					
car, solo, small, petrol, free parking					
Inhabitants	0.361	0.533	0.894	0.407	1.085
Commuters	0.261	0.497	0.758	0.407	0.949
car, solo, small, petrol, paid parking					
Inhabitants	0.361	0.533	0.894	0.407	1.085
Commuters	0.261	0.497	0.758	0.407	0.949
car, solo, small, diesel, free parking					
Inhabitants	0.326	0.556	0.881	0.435	1.073
bust/tram (inhabitants)	0.080	0.08	0.160	0.020	0.501
Off-peak					
car, solo, small, petrol, free parking					
Inhabitants	0.359	0.188	0.546	0.047	0.694
bus/tram (inhabitants)	0.271	0.104	0.375	0.016	0.797
Volume and composition of traffic	mio pkm	Share (%)	% carpool	Speed (km/h)	
Peak, private	2.969	35.5	33	40	
Peak, public	2.372	28.2		36	
Off-peak, private	2.446	29.1	26	50	
Off-peak, public	0.623	7.4		44	
Tax revenue (mio ECU/day)					
Private	1.710				
Public	0.213				
Non-congestion External costs (mio ECU/day)	0.374				

Combining these optimal prices gives lower overall volumes of transport: a decrease of 9%. In addition there are important shifts from private to public transport in the peak. Public transport increases by 29 % in the peak while private transport in the peak is reduced by 23%. Car pooling in the peak increases from 29% of passengerkilometre in the reference to 33% under optimal pricing.

3. Relative efficiency of policy scenarios

Table 3 gathers some of the main results of the counterfactual equilibria, and compares them with the reference situation. The scenarios are ranked according to relative welfare gain. The maximal welfare gain obtained in the full optimum scenario receives an index 100%.

The performance of the different instruments differs strongly. It is clear that optimising public transport pricing will generate only modest relative welfare gains (11%, 2nd column in table 3). The major sources of concern are the excessive levels of peak traffic in the urban areas and the large subsidy to drivers with free access to parking. Simply charging all drivers for the full resource costs of their trips, as is done in the parking charges scenario, leads to a relative welfare gain of 32% of the maximal welfare gain. Introducing a simple cordon toll is relatively efficient (53.5%).

Table 3: Key results of counterfactual equilibria

	% relative welfare gain	traffic level (index)	% peak, private traffic	% peak, public traffic	% off-peak, private traffic	% off-peak, public traffic	Non-congestion external cost (index)	Average peak hour speed (km/h)
REF	0	1	41.6	19.9	30.7	7.9	1	23
SCC	0	1	41.7	19.9	30.5	7.9	99	23
OPT	10.7	1.04	39.3	24.4	29.3	7.0	101	24
PC	32.5	0.98	41.4	21.5	26.8	10.2	96	26
CP	53.5	0.98	37.2	24.1	30.4	8.3	96	33
FO	100	0.91	35.3	28.2	29.1	7.4	88	40

The changes in the overall traffic level are small, except for the full optimum. Traffic decreases, except in the optimal public transport prices scenario. There, public transport is subsidised more than in the reference situation, because of the large undertaxation of private transport. Consequently the money price of transport decreases, and traffic demand grows. The effect on external costs remains positive however, because of the shift from private to public transport (which, per person, has a smaller effect on overall congestion).

All counterfactual equilibria show a lower share of peak period private traffic, an increase of the share of peak period public transport, a decrease of the off-peak private share and an increase of the off-peak public transport share. The size of the changes in market shares differs strongly over scenarios. In the parking charges scenario, the decrease in off-peak private traffic is large. The share of public transport increases sharply, in peak as well as in off-peak hours. This in turn has positive effects on the congestion conditions, hence the substantial decrease in external costs in this scenario.

The efficiency gains from placing a cordon around the city are rather limited (53% of the maximal gain). This is due to the decrease in generalised transport costs for inhabitants, when commuters reschedule their trips, switch modes, or make less trips because of the cordon toll. Moreover, this scenario also has adverse distributional effects. The consumer surplus of inhabitants increases, while that of commuters decreases sharply when all cordon toll revenue is shared equally as has been assumed here.

V. CONCLUSIONS

A partial equilibrium model for studying urban transport markets was developed to trade-off different policy instruments addressing environmental and transport externalities. The simple model was shown useful to compute orders of magnitude of optimal second best pricing strategies. The illustration for Brussels yielded some three policy conclusions of interest.

First it was shown that charging correctly for all resource costs, by charging parking resource costs to all car travellers, has positive and beneficial effects on the transport situation. This is not only because subsidies decrease, but also because congestion externalities decrease. Fully charging for resource costs is an important step towards social cost pricing.

Secondly, marginal external costs estimated in the present (inefficient) equilibrium are a bad guide for the reform of taxes on car use because after the imposition of the optimal levies, congestion levels are strongly reduced and marginal external costs may be reduced with 50% or more compared to the reference equilibrium.

Thirdly, as long as pricing of car use can be adapted, an important part of the total potential welfare gain can be realised. When however only environmental standards on cars or only public transport pricing can be used as policy instruments, only a small part of the total potential welfare gain is attainable.

Of course the model shown was simple and can be extended in several directions. An obvious extension is to represent the full network structure and to compute optimal cordon tolls and public transport prices for all links. This is a straightforward generalisation of the theoretical model but is less obvious in terms of computation if optimal second best tolls have to be computed. Another generalisation is the use of a dynamic model with explicit modelling of car ownership and discrete consumer choice representation. This will again make the optimisation of instruments much more difficult. Another problem in the use of a dynamic model is the formation of expectations on policy.

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