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**Taxation of car ownership, car use and public
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choice numerical optimisation model**

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Taxation of car ownership, car use and public transport: insights derived from a discrete choice numerical optimisation model

by

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ABSTRACT

In this paper we study the taxation of car ownership, car use and public transport in the presence of externalities within the framework of a discrete/continuous choice model. We first derive optimal taxes in a simplified setting, emphasizing the specific role of fixed car ownership taxes and the relevance of public transport demand by non-car owners for the optimal tax structure. A numerical optimisation model is then constructed to study welfare-optimal public transport fares and two-part tariffs on ownership and use of gasoline and diesel cars in Belgium. Results are as follows. First, we find that the current differences in tax treatment between diesel and gasoline car ownership and use cannot be justified on the basis of external cost and budgetary considerations. Efficient pricing requires substantial increases in the relative user tax on diesel cars as compared to gasoline cars; optimal fixed taxes are substantially below current levels and only marginally differ between car fuel types. Second, if for political or technical reasons variable car taxes cannot be optimally adjusted, large differences in fixed car taxes do result. The same holds if the government uses kilometre taxes as the main variable tax instrument. Third, the results of a series of marginal tax reform exercises suggest that a shift from gasoline towards diesel taxation is welfare improving, both for fixed and variable taxes. Somewhat surprisingly, a shift from fixed towards variable taxes is not necessarily welfare-improving: it is for diesel, but not for gasoline cars.

Keywords: transport externalities, optimal taxation, two-part tariffs

JEL-codes: H21, H23, R41

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1. Introduction

There now exists a substantial literature on optimal pricing and regulation of transport externalities, both in a first-best and in a second-best framework. Important early contributions include, among others, Vickrey (1969), Keeler and Small (1977), and Glaister and Lewis (1978). More recent research has extended this work, among others, to a general equilibrium framework (Mayeres and Proost (1997)), to account for endogenous departure times (Arnott et al. (1993)), and to incorporate optimal public transport supply (e.g., Viton (1983), De Borger and Wouters (1998)). Moreover, restrictions on the pricing instruments that have been studied include the impossibility to use time-differentiated taxes (Arnott et al. (1993), Verhoef et al. (1995) and De Borger et al. (1997)) and the impossibility to tax all links on simple transport networks (Van Dender (2001), Verhoef (2002)). Finally, the welfare effects of specific policy instruments have been evaluated using detailed numerical models (see, e.g., Kraus (1989), De Borger et al. (1997), Mayeres (2000), Parry and Small (2002)).

Interestingly, with very few exceptions (see below) the available studies ignore issues of car ownership and, as a consequence, they do not capture the inherent two-part tax structure that exists in most countries. Indeed, almost all governments separately tax car ownership (e.g., through annual vehicle taxes) and car use (e.g., through fuel taxes). In a sense the focus on various variable car tax instruments (fuel taxes, kilometre taxes, electronic road pricing, etc.) is not surprising, because under a wide range of circumstances variable taxes are more efficient at internalising external costs than, e.g., fixed annual vehicle taxes. However, there are at least three reasons why incorporating the ownership decision and the role of fixed car taxes may be important. First, fixed annual taxes on vehicles may play an important role in second-best situations when the government does not dispose of the variable tax instruments needed to adjust taxes to the relevant marginal external costs (see Chia et al. (2001), De Borger (2001)). Second, as suggested by, e.g., Rouwendal and Verhoef (2003), the two-part tax structure is quite relevant when governments face budgetary constraints. Third, the optimal tax treatment of different fuel types for cars, a discussion currently widely debated in a number of European countries, cannot be satisfactorily studied by exclusively focusing on car use, ignoring ownership issues (Mayeres and Proost (2001)). Ownership taxes affect both the composition of the car stock and the intensity of car use, and have therefore strong implications for the tax revenues on different fuel types.

The purpose of this paper is to study the tax treatment of car ownership, car use and public transport demand within the framework of a discrete choice numerical optimization model. The theoretical structure of the model extends De Borger (2001) for the presence of public transport options, which turn out to play a relevant role in the optimal tax structure. Consumers are assumed to have the choice between two types of car¹; alternatively, they can decide not to own a car. Public transport is assumed to be available to both car owners and non-owners. Consumers decide jointly on car ownership and on the demand for kilometres by car and by public transport. All transport services are assumed to generate externalities. The government is assumed to be budget-constrained and to have five instruments: fixed ownership and variable user taxes on the two car types, and public transport fares. The theoretical results show that the availability of public transport for people that do not own cars tends to raise optimal variable taxes above marginal external cost. Moreover, public transport pricing strongly interacts with the fixed user taxes on cars when variable car user taxes for some reason cannot be optimally adjusted to external costs.

A more elaborate numerical version of the model is then implemented to analyze in detail the tax treatment of different car types and public transport use on the basis of Belgian data. Both optimal tax results and the effects of a number of specific tax reforms are reported. First, we study optimal taxation of cars and public transport under various alternative restrictions on the variable tax instruments. Appropriate implementation of such restrictions allows us to mimick optimal kilometre taxes, optimal fuel taxes, etc. Moreover, we consider the optimal policy mix within the set of currently used tax instruments, assuming the government wants to generate the observed amount of tax revenues. Finally, we look at the role of fixed car taxes and public transport fares when variable car taxes cannot be optimally implemented for technical or political reasons.

The optimal tax results include the following. We find that the current differences in tax treatment between diesel and gasoline cars and their use appear to be unjustified on the basis of external cost and budgetary considerations alone². Efficient pricing requires substantial increases in the relative user tax on diesel cars as compared to gasoline cars; optimal fixed taxes are substantially below current levels and only marginally differ between fuel types. Large differences in fixed car taxes do result if variable taxes cannot be optimally adjusted. Welfare comparisons of the various optima suggest that substantial welfare gains

¹ We have gasoline versus diesel cars in mind in this paper, but cars incorporating 'clean' versus 'dirty' emission technologies would be an obvious alternative interpretation.

² Currently in Belgium the fuel tax on gasoline is substantially higher than on diesel, whereas the annual vehicle tax on diesel cars is much above that on cars using gasoline.

can be realised by an optimal differentiation of fixed car taxes although, not surprisingly, much larger gains can be realised by allowing time differentiated (peak versus off-peak) variable taxes.

Second, the numerical model is also used to simulate the marginal welfare effects of various revenue-neutral transport policy tax reform packages. It is found that a policy package that combines peak road pricing with revenue recycling by either raising public transport subsidies or reducing gasoline taxes has the highest marginal welfare effects. A shift from gasoline towards diesel taxation is welfare improving, both for fixed and variable taxes. Surprisingly, a shift from fixed towards variable taxes is not generally welfare-improving; it is for diesel, but not for gasoline.

At least four recent papers have studied issues related to those analysed in this paper. First, Chia et al. (2001) also study the relative merits of fixed and variable transport taxes, but they do so in a totally different framework. A threshold income level divides the population in two segments. People with lower incomes exclusively use bus services, higher-income people are car owners; all their transport is done by car. The latter assumption (car owners travelling exclusively by car), is quite unrealistic in a European context, where a large fraction of public transport users (especially for commuting trips) actually do own a car. Moreover, only one car type is considered so that the relation between ownership and fuel taxes for different car types cannot be studied. Finally, they do not study restrictions on tax instruments. Second, Mayeres and Proost (2001) numerically investigate the implications of a particular budgetary-neutral policy proposal, consisting of changing the relative ownership taxes on gasoline and diesel cars. However, the car ownership decision is modelled fairly ad hoc and not based on an explicit (discrete choice) optimisation framework; moreover, it is assumed that ownership implies some committed consumption of car kilometres³. Finally, unlike in their study, we consider both optimal taxation and tax reform exercises, and look at a richer set of transport tax reforms. Third, Verhoef and Rouwendal (2003) explicitly incorporate car ownership decisions in a model of pricing and investment on simple road networks. However, their focus is on issues of network financing, not on the tax treatment of different car types and the interaction with public transport availability. Finally, Fullerton and West (2001) analyse to what extent taxes on gas, engine size and vintage are able to mimic an optimal tax on car

³ On the other hand, Mayeres and Proost (2001) is more general than our approach in other respects: it is based on a formal general equilibrium model and it allows, at least in principle, to distinguish cars for personal use, cars for business use, and trucks.

emissions. However, they do not consider budgetary constraints and do not explicitly focus on the issue of fixed versus variable user taxes⁴.

This paper has a number of obvious limitations. First, despite the strong implied restrictions on substitution possibilities, we use the logit model of discrete choice throughout the paper. The main reason is analytical tractability (see De Borger (2001) for discussion). Second, the paper takes a clear partial equilibrium point of view: the existence of other distortive taxes (e.g., labour taxes) only enters via an exogenous shadow cost of funds; moreover, we ignore distributional concerns throughout. Third, we ignore some of the international complications associated with the currently used variable taxes: for example, by focusing on one country we ignore fuel tax competition between countries (see, e.g., De Borger et al. (2004), Evers et al. (2004)).

The structure of the paper is as follows. In Section 2 we present the theoretical model and interpret the resulting optimal tax structure. Section 3 describes the numerical optimisation model used for the empirical application. The construction of the reference situation based on Belgian data is explained in Section 4. In Section 5 we report optimal tax results under various constraints on the pricing instruments. A number of well-defined tax reform exercises are discussed in Section 6. Finally, Section 7 concludes.

2. Optimal taxation of car ownership, car use and public transport services in a model of discrete choice: theoretical background

The purpose of this section is to briefly extend the discrete/continuous choice optimal tax model described in De Borger (2001) to explicitly incorporate the demand for public transport services. This extension is useful for understanding the interaction between private and public transport in the numerical model presented in the next section. We focus in the discussion on the most relevant additional results and refer for earlier findings to the previous paper.

⁴ However, their analysis is quite relevant because the suggested tax mix boils down to a combination of imperfect variable user taxes (gas) and fixed annual charges (engine size, age). Interestingly, they find that 71% of the welfare gain under the Pigovian tax can be realised with a combined tax on size, gas and vintage; 62% is obtainable from a gas tax alone.

2.1. Structure of the model

We consider an economy with N identical individuals. Let there be two car types, diesel and gasoline cars. Consumers are assumed to have three options. They may choose between the two car types ($i=g,d$), or they may prefer not to own a car ($i=o$). In addition, both owners and non-owners are assumed to have access to public transport.

Indirect utility conditional on selecting alternative i (v_i) is specified as

$$v_i = V_i + u_i \quad (1)$$

where V_i are ‘universal’ indirect utility functions common to all individuals. The u_i are individual-specific components that reflect idiosyncratic taste differences. The conditional indirect utility associated with owning a gasoline or diesel car is given by

$$V_i(p_i, p_b, y - F_i, E) = \text{Max } u(x_c^i, 0, x_b^i, z^i, E) \quad \text{s.t.} \quad p_i x_c^i + p_b x_b^i + z^i = y \quad (i = g, d) \quad (2)$$

where fixed taxes on the two car types are denoted by F_i ($i=g,d$). The variable prices per kilometre are given by p_g and p_d . Public transport price is denoted p_b . Conditional demand for public transport by owners of a diesel or gasoline car is given by x_b^d and x_b^g , respectively. Demands for car use are denoted similarly by x_c^g and x_c^d for owners of a gasoline and diesel car, respectively. The consumption of the numeraire composite commodity, given that one owns a car of type i , is z^i . The externality level E is treated by the individual as exogenously given. Finally, conditional utility of not owning a car is

$$V_o(p_b, y, E) = \text{Max } u(0, 0, x_b^o, z^o, E) \quad \text{s.t.} \quad p_b x_b^o + z^o = y \quad (3)$$

where x_b^o is the conditional demand for public transport by non-car owners, and z^o is their conditional demand for the numeraire.

Assuming that people choose the alternative that yields highest utility, i.e.,

$$v_i = \text{Max}(v_g, v_d, v_o) \quad (4)$$

and that the u_i are distributed Gumbel i.i.d., the associated probabilities of the three options are given by

$$\pi_i = \exp\left(\frac{V_i}{\mu}\right) / \left(\exp\left(\frac{V_g}{\mu}\right) + \exp\left(\frac{V_d}{\mu}\right) + \exp\left(\frac{V_o}{\mu}\right) \right) \quad i = g, d, o \quad (5)$$

where μ is a scale parameter of the joint distribution of the u_i (see Anderson et al. (1993)). Note that the probabilities of the three alternatives depend on fixed and variable prices and on externality levels:

$$\pi_i(p_g, p_d, p_b, y, F_g, F_d, E) \quad i = g, d, o \quad (6)$$

The conditional demand for kilometres can be derived from the conditional indirect utilities by Roy's identity. Demand for car and bus transport by owners of car owners are given by

$$\begin{aligned} x_c^i(p_i, p_b, y - F_i, E) \\ x_b^i(p_i, p_b, y - F_i, E) \end{aligned} \quad i = g, d \quad (7)$$

Similarly, public transport demand by non-owners is given by

$$x_b^o(p_b, y, E) \quad (8)$$

The externality E is the result of the total demand for car and public transport use in the population

$$E = f(X_c^g, X_c^d, X_b) \quad (9)$$

where

$$\begin{aligned} X_c^i &= N\pi_i x_c^i \quad i = g, d \\ X_b &= N(\pi_g x_b^g + \pi_d x_b^d + \pi_o x_b^o) \end{aligned} \quad (10)$$

and, obviously, $\pi_o = 1 - \pi_g - \pi_d$.

The government's problem can now be formulated as choosing the variable prices p_g, p_d, p_b and the fixed car taxes F_g, F_d so as to maximise the expected value of maximum utility (see Anderson et al. (1993)):

$$W = N\mu \ln \left\{ \exp\left(\frac{V_g(p_g, p_b, y - F_g, E)}{\mu}\right) + \exp\left(\frac{V_d(p_d, p_b, y - F_d, E)}{\mu}\right) + \exp\left(\frac{V_o(p_b, y, E)}{\mu}\right) \right\} \quad (11)$$

subject to the budget restriction

$$N \left\{ \sum_{i=g,d} \pi_i [(p_i - c_i)x_c^i + F_i] + [(p_b - c_b)(\pi_g x_b^g + \pi_d x_b^d + \pi_o x_b^o)] \right\} = G \quad (12)$$

where c_i ($i=g, d, b$) stands for the marginal resource costs of car and bus kilometres. Note that the budget constraint is imposed on the transport sector as a whole and not specifically on the public transport sector. Moreover, G incorporates the fixed costs associated with public

transport supply. In other words, public transport costs are assumed to be linear with constant marginal costs. The Lagrange multiplier associated with the government budget constraint is denoted by λ .

2.2. Optimal pricing rules: all tax instruments available

The derivation of the optimal pricing rules follows the same methodology as in De Borger (2001). The extension is briefly summarised in Appendix 1 to the current paper. Assuming, to keep the expressions transparent, that the marginal utility of income is independent of the ownership choice and that income effects of the conditional demands are zero, the following results emerge⁵:

$$p_g - c_g - \theta_g = \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_b^g}{\partial p_g} \frac{\partial \hat{x}_c^d}{\partial p_d}}{Z} \quad (13)$$

$$p_d - c_d - \theta_d = \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_b^d}{\partial p_d} \frac{\partial \hat{x}_c^g}{\partial p_g}}{Z} \quad (14)$$

$$p_b - c_b - \theta_b = - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^g}{\partial p_g} \frac{\partial \hat{x}_c^d}{\partial p_d}}{Z} \quad (15)$$

$$F_g = - \left(\frac{m - \lambda}{\lambda} \right) \frac{1}{\pi_o m} - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^d}{\partial p_d} \left[\frac{\partial \hat{x}_b^g}{\partial p_g} x_c^g - \frac{\partial \hat{x}_c^g}{\partial p_g} (x_b^g - x_b^o) \right]}{Z} \quad (16)$$

$$F_d = - \left(\frac{m - \lambda}{\lambda} \right) \frac{1}{\pi_o m} - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^g}{\partial p_g} \left[\frac{\partial \hat{x}_b^d}{\partial p_d} x_c^d - \frac{\partial \hat{x}_c^d}{\partial p_d} (x_b^d - x_b^o) \right]}{Z} \quad (17)$$

where m is the marginal utility of income, and the notation \hat{x} refers to compensated demands. The θ_i ($i=g,d,b$) are the full marginal external costs associated with an increase in demand for car kilometres by gasoline cars, diesel cars and public transport. Finally, the

⁵ These assumptions are needed to simplify the results and to facilitate the interpretation. In the numerical model, they obviously are not maintained.

Slutsky equation guarantees that $Z > 0$. Both the marginal external costs θ_i ($i=g,d,b$) and the term Z are defined and discussed in detail in Appendix 1.

Turning to the results, first consider the variable taxes on cars and public transport. If the model did not include transport options for non-car users ($x_b^o = 0$), then all variable taxes are equal to marginal external cost, and fixed taxes are just used to make up for whatever extra budget is required:

$$F_i = -\left(\frac{m-\lambda}{\lambda}\right)\frac{1}{\pi_o m}, i = g, d$$

The intuition is that, although the fixed taxes can be avoided by changing ownership type, conditional on the car type selected they act like a lump-sum instrument. Hence, at the margin they are more efficient at raising revenues, and there is no revenue-raising role for the variable taxes (see Chia et al. (2001)).

Interestingly, however, the availability of transport options for people that do not own a car implies deviations from marginal external cost pricing for all transport services. Assuming that car and bus use by car owners are substitutes and that the budget constraint is sufficiently stringent (so that the shadow price of the constraint exceeds the private marginal utility of income), it follows from (13)-(14)-(15) that all variable taxes actually exceed marginal external cost. It is the absence of a conditional lump-sum tax instrument for non-car owners that drives this result. It implies that public transport fares now do have a revenue-raising role⁶. Moreover, to the extent that variable car taxes contribute to induced extra tax revenues on public transport (i.e., with nonzero cross-price elasticities of conditional demands for public transport by car owners with respect to variable car prices), the same holds for both variable car taxes.

Fixed taxes are similarly affected by the availability of public transport. To see this most directly note that, by inserting (13)-(14)-(15) into the fixed tax rules (16)-(17), the latter can be written as:

$$F_i = -\left(\frac{m-\lambda}{\lambda}\right)\frac{1}{\pi_o m} - \left[(p_i - c_i - \theta_i)x_c^i + (p_b - c_b - \theta_b)(x_b^i - x_b^o) \right] \quad i = g, d$$

Not surprisingly, raising variable car taxes above marginal external cost allows fixed taxes to be reduced. Raising public transport fares allows fixed tax reductions as long as public transport use by car owners exceeds that by non-owners. If public transport use by car owners

⁶ Observe that public transport taxes above marginal external cost may still imply large subsidies because of the fixed cost incorporated in the budget constraint G.

is small, then raising public transport fares generates insufficient extra revenue on car owners, and the fixed fee is raised to increase the probability of non-ownership.

What determines the fixed tax difference between gasoline and diesel cars? Note that the difference can be written as:

$$F_g - F_d = (p_b - c_b - \theta_b)(x_b^d - x_b^g) - (p_g - c_g - \theta_g)x_c^g + (p_d - c_d - \theta_d)x_c^d$$

It follows that, if all variable taxes equalled marginal external cost there would be no reason to have different fixed taxes at all. As seen before, however, the availability of public transport for non-car owners implies deviations from marginal cost pricing and, hence, unequal optimal fixed taxes. The optimal fixed tax for a given car type is inversely related to the variable tax revenues for this car type and to the conditional demand for public transport by its owners. The reason is simply that a large conditional demand for bus use implies that more public transport revenues are generated on owners of this car type. Suppose, for example, that gasoline generates more variable tax revenues (this depends on various elasticities, see (13)) and that conditional bus demand is higher for gasoline car owners than for diesel owners, then the optimal fixed tax on diesel exceeds the one on gasoline.

2.3. Restrictions on variable car taxes

As noted in the introduction, fixed taxes are likely to play a much more pronounced role in correcting external costs if the government faces (technical or political) restrictions on the variable tax instruments. If the variable tax instruments do not allow differentiation according to pollution (e.g., kilometre taxes) and safety (e.g., fuel taxes) characteristics, fixed taxes can be useful to internalise part of the relevant externalities. Moreover, even if it were technically possible, it may not be politically feasible to charge the optimal variable taxes. Fixed tax differences may then have a potentially important role to play.

In this subsection we therefore look at the role of fixed taxes and public transport prices when governments are unable to implement the appropriate variable car taxes. For simplicity, we limit the discussion to one case, viz. the case of optimal fixed taxes and public transport fares conditional on exogenous and sub-optimal variable car taxes⁷. Adapting the

⁷ Note that many other types of restrictions could be considered, such as the inability to differentiate variable taxes between car types; this would be relevant if the government used a kilometre tax as its main variable instrument. In general, however, the derivation of the optimal tax structure under different sets of restrictions is quite complex and, unfortunately, does not lead to expressions that are easy to interpret. We therefore limit the theoretical discussion to one specific example and leave several other relevant alternatives to the numerical analysis in the next sections.

derivation reported in De Borger (2001, Appendix 2) for public transport availability, one easily shows the following optimal tax rules (where, for simplicity, we have again assumed constant marginal utilities of income, independent of the car type selected):

$$p_b - c_b - \theta_b = \frac{\left[\left(\frac{m-\lambda}{\lambda} \right) x_b^o \right] - (\bar{p}_g - c_g - \theta_g) \pi_g \frac{\partial \hat{x}_c^g}{\partial p_b} - (\bar{p}_d - c_d - \theta_d) \pi_d \frac{\partial \hat{x}_c^d}{\partial p_b}}{M} \quad (18)$$

$$F_g = - \left(\frac{m-\lambda}{\lambda} \right) \frac{1}{\pi_o m} - \left(\frac{m-\lambda}{\lambda} \right) \frac{x_b^o (x_b^g - x_b^o)}{M} - (\bar{p}_g - c_g - \theta_g) \left[x_c^g - \frac{\pi_g \frac{\partial \hat{x}_c^g}{\partial p_b} (x_b^g - x_b^o)}{M} \right] + (\bar{p}_d - c_d - \theta_d) \left[\frac{\pi_d \frac{\partial \hat{x}_c^d}{\partial p_b} (x_b^g - x_b^o)}{M} \right] \quad (19)$$

$$F_d = - \left(\frac{m-\lambda}{\lambda} \right) \frac{1}{\pi_o m} - \left(\frac{m-\lambda}{\lambda} \right) \frac{x_b^o (x_b^d - x_b^o)}{M} - (\bar{p}_d - c_d - \theta_d) \left[x_c^d - \frac{\pi_d \frac{\partial \hat{x}_c^d}{\partial p_b} (x_b^d - x_b^o)}{M} \right] + (\bar{p}_g - c_g - \theta_g) \left[\frac{\pi_g \frac{\partial \hat{x}_c^g}{\partial p_b} (x_b^d - x_b^o)}{M} \right] \quad (20)$$

where the $\bar{p}_i, i = g, d$ are the suboptimal and exogenously fixed variable car taxes, and

$$M = \pi_g \frac{\partial \hat{x}_b^g}{\partial p_b} + \pi_d \frac{\partial \hat{x}_b^d}{\partial p_b} + \pi_o \frac{\partial \hat{x}_b^o}{\partial p_b} < 0 \quad (21)$$

Results are easily interpreted. The optimal public transport fare (see (18)) just reflects a standard and well known second best argument. If variable car taxes are insufficient to cover marginal external costs, optimal public transport fares decline to the extent that this reduces conditional demands for car kilometres. If car use were substantially under-priced, one can easily justify public transport fares largely below marginal external cost, even with a stringent budget constraint.

The fixed car taxes are quite complex. To develop some intuition suppose, for the sake of the argument, that gasoline car taxes reflect marginal external costs but that diesel car use is severely under-taxed. The fixed annual fee on diesel cars then also serves to compensate for the excessive externalities generated by diesel car use. As a consequence, one expects the fixed fee on diesel to rise. Expression (20) shows that this is indeed the case, unless public transport use by owners of this car type is very small. Indeed, in the extreme case that bus demand by diesel owners is negligible and bus demand by non car owners is large, the fixed

fee on diesel cars may in fact go down. The reason is to be found in the effects of too low diesel taxes on public transport fares. It follows from (18) that the low diesel taxes reduce optimal public transport fares. In the extreme case that bus use by diesel car owners is limited and bus demand by non car owners is very large, the revenue losses on owners of diesel cars due to reduced public transport fares are negligible and the revenue gains on public transport users rise strongly; as a consequence, in the extreme the fixed diesel tax may go down despite the under-pricing of diesel use.

To investigate the determinants of the difference in fixed annual taxes, note that this difference can be written as:

$$\begin{aligned}
F_g - F_d = & \left(\frac{m - \lambda}{\lambda} \right) \frac{x_b^o}{M} (x_b^d - x_b^g) - (\bar{p}_g - c_g - \theta_g) \left[x_c^g - \frac{\pi_g \frac{\partial \hat{x}_c^g}{\partial p_b} (x_b^g - x_b^d)}{M} \right] \\
& + (\bar{p}_d - c_d - \theta_d) \left[x_c^d - \frac{\pi_d \frac{\partial \hat{x}_c^d}{\partial p_b} (x_b^d - x_b^g)}{M} \right]
\end{aligned} \tag{22}$$

Relative fixed taxes depend on the relative under-pricing of gasoline versus diesel as well as on the relative use of public transport by owners of diesel and gasoline cars. A few simplifying cases help to illustrate the result. First, if the conditional demand for public transport by owners of both car types were equal, the relative fixed fees only depend on the degree of under-pricing relative to marginal external cost. Given that diesel is generally believed to imply larger marginal external costs than gasoline on a per kilometre basis (see Mayeres and Van Dender, 2001), this may justify the fact that countries that for some reason strongly under-tax diesel fuel (e.g., Belgium; the Netherlands, France, Italy, etc.) impose substantially higher ownership taxes on diesel cars. Second, if relative public transport uses are not equal, some corrections are needed. Suppose for the sake of the argument that gasoline were taxed at marginal external cost but that diesel were taxed at a much lower rate, and that the conditional demand for bus use by owners of gasoline cars exceeds that of diesel owners. Two opposing effects are at play then. On the one hand raising the fixed tax on diesel relative to gasoline is desirable (first term on the right hand side of (22)) under the stated assumptions, because it shifts the car stock towards more gasoline cars, which generates more public transport demand. On the other hand, however, raising the fixed tax on gasoline cars is

desirable to compensate for the revenue losses due to variable tax under-pricing (final term on the right hand side of (22)).

To conclude this section, note that previous theoretical results were derived under a number of simplifying assumptions, including the absence of income effects in conditional demands and the absence of peak versus off peak differentiation. Moreover, it is also obvious that optimal tax rules easily become relatively complex when restrictions on tax instruments are imposed. Therefore, rather than theoretically analysing various other types of restrictions, we proceed in the next section to the development of a slightly extended numerical version of the model that will allow a numerical illustration of optimal taxes under a wide variety of potential restrictions on tax instruments.

3. The numerical model

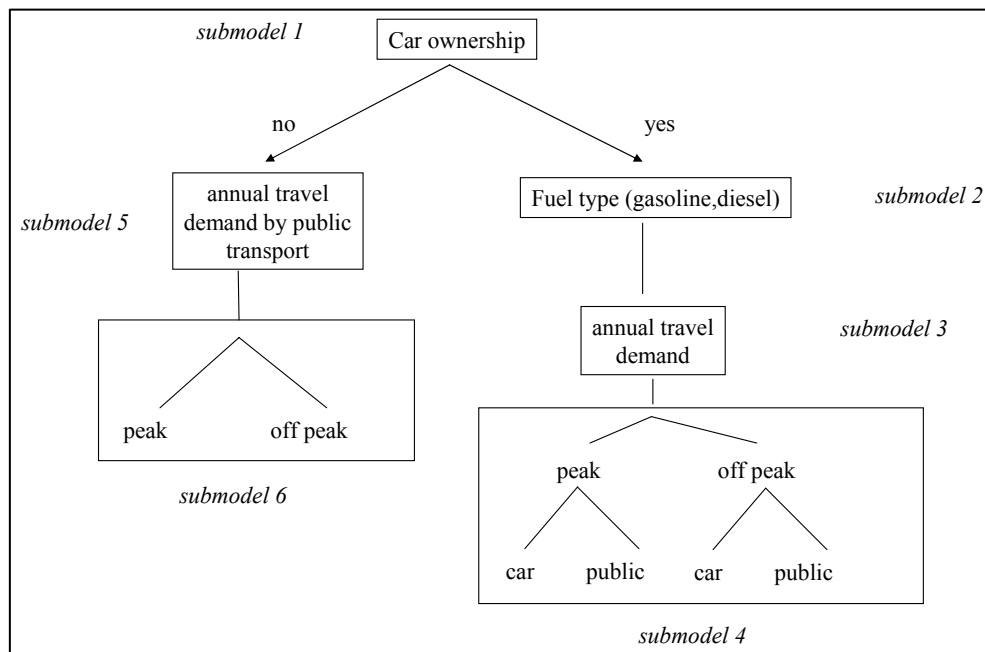
In this section we present the numerical model that is used to study the optimal tax treatment of car ownership, car use and public transport in Belgium. The numerical model closely follows the design of the theoretical structure presented before. However, to make the numerical analysis more realistic and allow a richer set of tax policies, the following extensions are incorporated. First, to impose more structure on the model we opt for a nested discrete choice structure, unlike in the theoretical analysis. Second, apart from distinguishing two types of car (diesel and gasoline cars), we also distinguish between peak and off-peak traffic. This is important in order to capture the congestion externality in a realistic way and to allow analysis of congestion-related pricing policies. Third, we marginally adjust the objective function for two reasons: (i) it allows us, apart from analysing optimal tax structures in the presence of a formal budget constraint, to also consider optimal taxes when tax revenues get an exogenous weight (relative to the monetary evaluation of consumer welfare) in the objective function; (ii) it allows us to accommodate the inclusion of the most important externalities typically associated with transport services: congestion, air pollution and accidents.

In the remainder of this section we describe the structure of the numerical model. We first discuss how the various discrete and continuous choices faced by the consumer are modelled. Next, we briefly describe the tax instruments that are included, the modelling approach for the three types of externalities and the specification of the objective function.

3.1. Consumer behaviour

There are N identical households. Each household chooses (i) whether to own a car or not, (ii) the fuel type of the car and (iii) the annual mileage travelled by car and public transport, with a distinction between peak and off-peak transport. To model the household's choice options, we consider the decision structure presented in Figure 1. A first sub-model describes the decision to own a car or not. Conditional on car ownership, the choice of the fuel type (gasoline, diesel) of the car (sub-model 2) is determined jointly with overall annual travel demand (sub-model 3). Finally, conditional on the choice of car type, we consider the demand for kilometres by car and by public transport, and the allocation to peak and off-peak demand (sub-model 4). This latter process is modelled as a continuous choice. If the household is predicted not to own a car, annual travel demand by public transport is predicted (sub-model 5). Finally, allocation over the peak and off-peak period (sub-model 6) is again modelled as a continuous choice.

Figure 1: Decision structure



We start a more detailed description with **sub-model 2**. The deterministic component of indirect utility, conditional on ownership of a car of type i ($i=g,d$), is specified as (based on De Jong, 1990):

$$V_i = \left[\frac{1}{\beta_i^c} \exp(\delta_i^c - \beta_i^c P_i^c) + \frac{1}{1 - \alpha_i^c} (Y - K_i - F_i)^{1 - \alpha_i^c} \right] / \xi_{i,ref}^c \quad (23)$$

where P_i^c is the generalised price of travel for households owning a car of type i and Y represents generalised income. K_i and F_i are the annual fixed resource cost and the annual fixed tax for a car of type i . Finally, α_i^c , β_i^c and δ_i^c are parameters. We express indirect utility in monetary terms by dividing by $\xi_{i,ref}^c$, the reference marginal utility of income. Assuming the stochastic components of conditional indirect utility terms to be Gumbel i.i.d. we obtain the probability of choosing a car of type i :

$$\pi_i^c = \exp(V_i / \mu_0) / \left(\sum_{k=g,d} \exp(V_k / \mu_0) \right) \quad (24)$$

where μ_0 is a scale parameter of the joint distribution of the stochastic terms. The aggregate utility of owning a car is the expected value of maximum conditional indirect utility:

$$W^c = \mu_0 \ln \left(\sum_{k=g,d} \exp \left(\frac{V_k}{\mu_0} \right) \right) \quad (25)$$

Simultaneous with the choice of car type in sub-model 2, conditional travel demand by car owners is determined in **sub-model 3**. Applying Roy's identity to the conditional indirect utilities (23) yields the following conditional travel demand functions for households owning a car of type i :

$$X_i^c = \exp(\delta_i^c - \beta_i^c P_i^c) (Y - K_i - F_i)^{\alpha_i^c} \quad (26)$$

Households owning a car are assumed to have a choice between car and public transport use in the peak and off-peak period. In order to incorporate this choice, **sub-model 4** first specifies P_i^c and X_i^c as CES aggregates defined on peak and off-peak prices and quantities (see Keller, 1976). These are in turn specified as CES aggregates defined on car and public transport prices and quantities. The above implies that demand for passenger kilometres by mode j ($j = \text{car, public}$) in period t ($t = \text{peak, off-peak}$), conditional upon ownership of a car of type i can be written as:

$$x_{i,t,j}^c = X_i^c \gamma_{i,t}^{1,c} \gamma_{i,t,j}^{0,c} (P_i^c)^{\sigma_i^{2,c}} (P_{i,t}^{1,c})^{(\sigma_i^{1,c} - \sigma_i^{2,c})} (P_{i,t,j}^{0,c})^{-\sigma_i^{1,c}} \quad (27)$$

Here $\sigma_i^{2,c}$ is the elasticity of substitution between peak and off-peak transport, for households owning a car of type i . Similarly, $\sigma_{i,t}^{1,c}$ is their elasticity of substitution between car and public transport in period t . The $\gamma_{i,t}^{1,c}$ and $\gamma_{i,t,j}^{0,c}$ are weighting parameters associated with the two CES functions. Moreover, $P_{i,t,j}^{0,c}$ is the generalised price of a passenger kilometre (pkm) travelled by mode j in period t if one owns a car of type i . The generalised price equals the sum of the resource costs, variable taxes and time costs per pkm. The time costs depend on total road traffic volume. Finally, (27) contains two CES price indices. First,

$$P_i^c = \left[\sum_{t=peak,offpeak} \gamma_{i,t}^{1,c} (P_{i,t}^{1,c})^{1-\sigma_i^{2,c}} \right]^{\frac{1}{1-\sigma_i^{2,c}}} \quad (28)$$

is the CES price index for travel if one owns a car of type i , and second

$$P_{i,t}^{1,c} = \left[\sum_{j=car,public} \gamma_{i,t,j}^{0,c} (P_{i,t,j}^{0,c})^{1-\sigma_{i,t}^{1,c}} \right]^{\frac{1}{1-\sigma_{i,t}^{1,c}}} \quad (29)$$

is the CES price index for travel in period t if one owns a car of type i .

Moving to the top of the decision structure (**sub-model 1**) we define the deterministic component of the indirect utility of not owning a car as:

$$W^{nc} = \left[\frac{1}{\beta^{nc}} \exp(\delta^{nc} - \beta^{nc} P^{nc}) + \frac{1}{1-\alpha^{nc}} Y^{1-\alpha^{nc}} \right] / \xi_{ref}^{nc} \quad (30)$$

where, as before, utility is expressed in monetary units by dividing by the relevant reference marginal utility of income ξ_{ref}^{nc} . Here P^{nc} is the generalised price of travel if one does not own a car and α^{nc} , β^{nc} and δ^{nc} are preference parameters. It is assumed that no fixed tax is levied on households that do not own a car. Under the assumptions underlying the logit model, the probability of owning a car is given by:

$$\rho^c = \exp(W^c / \mu_1) / \left(\exp(W^{nc} / \mu_1) + \exp(W^c / \mu_1) \right) \quad (31)$$

where μ_1 again is a scale parameter.

Sub-model 5 models travel demand of households not owning a car. Applying Roy's identity to the conditional indirect utility (30) yields the following conditional travel demand functions for households not owning a car:

$$X^{nc} = \exp(\delta^{nc} - \beta^{nc} P^{nc}) Y^{\alpha^{nc}} \quad (32)$$

Households not owning a car are assumed to travel by public transport only. In order to distinguish between peak and off-peak travel, **sub-model 6** specifies P^{nc} and X^{nc} as CES aggregates defined on peak and off-peak prices and quantities.

Finally, the expected value of maximum utility at the top of the decision tree can be written as:

$$U = \mu_1 \ln \left(\exp \left(\frac{W^c}{\mu_1} \right) + \exp \left(\frac{W^{nc}}{\mu_1} \right) \right) \quad (33)$$

3.2. Tax revenues

The government can impose variable taxes on car and public transport and fixed taxes on car ownership. Expected transport tax income T is given by:

$$T = N \rho^c \sum_{i=g,d} \pi_i^c \left(F_i + \sum_{\substack{t=peak, \\ off-peak}} \sum_{\substack{j=car, \\ public}} \left(F_i + (P_{i,t,j}^{0,c} - c_{i,t,j}^c) x_{i,t,j}^c \right) \right) \\ + N \rho^{nc} \sum_{\substack{t=peak, \\ off-peak}} \left(P_{t,public}^{0,nc} - c_{t,public}^{nc} \right) x_{t,public}^{nc} \quad (34)$$

where $c_{i,t,j}^c$ and $c_{t,public}^{nc}$ are marginal production costs per pkm, assumed to be constant.

3.3. Externalities

Congestion is included in the model through the generalised transport prices. These include the time cost associated with travel. The generalised prices directly appear in the conditional indirect utility function and therefore in the ownership probability and conditional demand functions.

The other external cost components (air pollution and accident costs) are assumed to generate constant marginal external costs, and to enter the welfare function in a separable and additive way. We define E as the monetary valuation of the expected external costs other than congestion:

$$E = N \rho^c \sum_{i=g,d} \pi_i^c \left(\sum_{\substack{t=peak, \\ off-peak}} \sum_{\substack{j=car, \\ public}} e_{i,t,j}^c x_{i,t,j}^c \right) + N \rho^{nc} \sum_{\substack{t=peak, \\ off-peak}} e_{t,public}^{nc} x_{t,public}^{nc} \quad (35)$$

with $e_{i,t,j}^c$ the marginal external air pollution and accident costs per pkm for mode j in period t if one owns a car of type i . The $e_{t,public}^{nc}$ is defined analogously.

3.4. The objective function

As previously suggested, we consider both taxation exercises with an exogenously imposed weight on government revenues and exercises with a formal budget restriction. First, in the former case, the objective function is specified as follows:

$$SW = NU + \psi T - E \quad (36)$$

It consists of three components: overall consumer utility, government tax revenues and external costs other than congestion. By varying ψ it allows us to exogenously incorporate, in a crude way, the efficiency costs of using the tax revenues raised on the transport market. External congestion costs are directly captured in the utility component via the generalised transport prices; external costs other than congestion are captured as part of the objective function. Second, in the case of a formal budget restriction we maximise $SW = NU - E$ subject to $T = \bar{T}$, where \bar{T} is exogenously chosen.

4. The reference situation: Belgium 2000

To calibrate the numerical model information on prices, taxes, car ownership shares and traffic flows is combined with estimates of behavioural parameters (various elasticities of demand and of the ownership shares) to calibrate the remaining model parameters. This procedure produces a reference situation that reflects an initial equilibrium with which the outcomes of various policies will be compared. In this section we provide more information on the assumptions and data underlying the construction of the reference situation. We review the most important hypotheses, present some important behavioural parameters, and provide data on marginal external costs.

4.1. Constructing the reference equilibrium: general assumptions

The reference equilibrium is constructed so as to represent, in a stylised way, the situation in Belgium in 2000. It was constructed under a number of implicit and explicit assumptions. First, all price, cost and demand data refer to average figures for urban and interregional traffic. Second, public transport is assumed to be an aggregate of rail, bus and tram transport. For simplicity, it is assumed that it does not generate congestion⁸. Third, the variable resource cost of car traffic is assumed to equal the net of tax fuel costs. To obtain the variable unit price, the variable tax per kilometre, which consists of the fuel tax in the reference equilibrium, is added on to the variable user cost. The fixed annual car ownership costs consist of interest and depreciation (a constant average life expectancy of 7 years is assumed). Annual fixed taxes consist of the annual vehicle tax and the annuity associated with the value-added tax levied on the price of the car at purchase and the registration tax. The variable unit price of public transport is simply the public transport fare.

4.2. Behavioural assumptions

The model is calibrated so as to obtain plausible price and income elasticities. As few reliable econometric estimates on demand elasticities are available for the specific Belgian case, we used values that were well within the range of those reported in the literature (see among others, De Jong (1990), De Jong and Gunn (2001), Oum et al. (1992), Goodwin (1992) and Train (1986)). Note that in some cases the estimates reported in the literature could not be directly transposed onto our model structure. For example, many published price elasticities of demand give the price sensitivity of total demand, not of conditional demands and ownership probabilities separately. Moreover, in cases where we did find separate conditional demand and ownership elasticities (e.g., De Jong (1990)) they were estimated within a slightly different model structure than ours. Finally, note also that the decision structure as presented in Figure 1 implies some a priori restrictions on the demand elasticities. For example, some conditional cross-elasticities are restricted to be zero. Moreover, conditional on owning a car of a given fuel type, the income and fixed cost elasticity of the different conditional demands for kilometres for the different modes and periods is the same. These

⁸ Obviously, although this seems plausible for rail and tram, it is not generally correct for bus transport to the extent that not all bus transport uses reserved bus lanes. In view of the rising share of bus kilometres on reserved lanes in urban areas and given our focus on relative fixed and variable instruments, we keep the above assumption as a working hypothesis.

constraints are of course not necessarily realistic; they are the price one has to pay for the gain in transparency and structure imposed on the model.

The calibrated demand elasticities used for the numerical analysis are presented in Tables 1 and 2. Table 1 reports elasticities of conditional demand with respect to money prices, fixed costs and income. The own price elasticities are within the range reported in the literature; in absolute value, they largely exceed cross-price elasticities. Moreover, own price effects are larger in the off-peak than in the peak. Generally speaking, the elasticities of conditional transport demand by diesel and gasoline car owners are quite similar. Public transport use by car owners is more elastic than that of non-car owners. Finally, the sensitivity of conditional demands with respect to fixed cost changes is very small, elasticities ranging from -0.03 to -0.05.

Table 2 reports the calibrated elasticity of the car ownership probabilities with respect to the money prices of car transport and fixed annual car costs, respectively. It shows that, plausibly, an increase in car costs of a particular car type has limited effects on the overall stock, but mainly influences its composition. Note that the calibration also implies that diesel car ownership is more elastic than gasoline car ownership⁹. The calibrated elasticities of car ownership with respect to the price of public transport are close to zero; they are not included in the table.

⁹ To get a better feel for this, we have performed some additional simulations with the model. For example, doubling the fixed gasoline car costs would increase the share of non-car owners from 19% in the reference equilibrium to approximately 21.2%. The composition of the car stock is affected much more strongly: the share of gasoline cars would fall from 59.4% to 7.7%. For diesel cars a doubling of the fixed costs would result in a diesel share of 1.1% in the car stock. Doubling the fixed costs of both diesel and gasoline cars would increase the share of non-car owners to 29%.

Table 1: Calibrated elasticity of conditional demand w.r.t. money prices, fixed car costs and income (reference equilibrium)

	Money price						Fixed costs		Money income
	Peak public	Off-peak public	Peak gasoline car	Off-peak gasoline car	Peak diesel car	Off-peak diesel car	Gasoline car	Diesel car	
<i>No car</i>									
peak public	-0.24	0.13							0.29
off-peak public	0.14	-0.36							0.29
<i>Gasoline car</i>									
peak car	0.03	0.01	-0.39	0.09			-0.03		0.33
off-peak car	0.01	0.03	0.06	-0.62			-0.03		0.33
peak public	-0.55	0.01	0.28	0.09			-0.03		0.33
off-peak public	0.01	-0.73	0.06	0.43			-0.03		0.33
<i>Diesel car</i>									
peak car	0.02	0.00			-0.36	0.09		-0.05	0.34
off-peak car	0.00	0.02			0.06	-0.59		-0.05	0.34
peak public	-0.56	0.00			0.27	0.09		-0.05	0.34
off-peak public	0.00	-0.74			0.06	0.42		-0.05	0.34

Table 2: Calibrated elasticity of car ownership probabilities w.r.t. money car prices and fixed car costs (reference equilibrium)

	Money price				Fixed costs	
	Peak gasoline car	Off-peak gasoline car	Peak diesel car	Off-peak diesel car	Gasoline car	Diesel car
Probability						
No car	0.02	0.03	0.02	0.03	0.07	0.07
Gasoline car	-0.12	-0.17	0.15	0.22	-0.37	0.48
Diesel car	0.16	0.23	-0.24	-0.33	0.49	-0.74

4.3. Marginal external costs

The model considers three externalities caused by transport: congestion, air pollution and accidents. Congestion is introduced through generalised transport prices that depend on average speed. The latter is determined endogenously using a speed-flow relationship that determines average speed as a function of the number of passenger car units per hour for each period considered. For the speed flow relationship we use the functional form of O'Mahony and Kirwan (2001) and calibrate its parameters on the basis of information on Belgian speeds and flows. The time cost per kilometre is the value of time per hour multiplied by the inverse of speed in km per hour. The value of time per hour is based on the review of the literature presented by Nellthorp et al. (2001)¹⁰.

The valuation of air pollution costs is based on De Nocker et al. (2001) who applied the methodology of the European ExternE project to Belgium. The costs include the effects on public health, agriculture and materials of eleven pollutants: CO₂, CH₄, N₂O, CO, NO_x, SO₂, VOC, PM, benzene, benzo(a)pyrene and 1,3 butadiene. The marginal external air pollution costs are calculated for the average gasoline and diesel car in Belgium in 2000. Air pollution costs are higher for diesel than gasoline cars due to the higher emissions of PM by diesel cars.

External accident costs are based on Mayeres et al. (1996). Under the assumption of constant accident risks, the marginal external accident costs are given by the product of the accident risk and the pure economic accident costs (net output losses, medical costs, police costs etc.). Three accident types are considered: fatalities, serious injuries and light injuries.

Table 3 gives an overview of the marginal external costs in the reference equilibrium. Note that the figures related to congestion are the direct marginal external congestion costs; the feedback effects (see Section 2) have not been captured in these figures¹¹. In the peak period congestion is the dominant external cost. In the off-peak pollution is relatively

¹⁰ For car transport the value of time used was 8.57 euro/h in the peak and 7.97 euro/h in the off-peak. For public transport the value of time is 6.1 euro/h in the peak and 5.02 euro/h in the off-peak.

¹¹ In the theoretical model (equations (13) to (15)) the optimal taxes are compared with the full rather than the direct marginal external costs. For the air pollution and accident externalities, there is no difference between the two, since they are not characterised by feedback effects. In the case of congestion there is a difference. The full marginal external congestion cost takes into account that a change in congestion itself affects transport demand and hence congestion; it therefore also has an impact on tax revenue and on pollution and accident costs. Comparing the full and direct marginal external congestion costs (MECC) of, for example, gasoline cars in the reference equilibrium, we found that the difference is large in the peak period (full MECC= 27.9 euro per 100 kilometre, direct MECC=47.3 euro per 100 kilometre) because the feedback parameter is quite large at the initial congestion levels. In the off-peak the difference is limited.

important, especially for diesel car use. Overall, diesel car use generates higher marginal external costs than gasoline.

Table 3: The marginal external costs in the reference equilibrium (euro/100 pkm)

	Air pollution		Accidents		Congestion		Total	
	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Gasoline car	0.77	0.77	0.38	0.38	47.3	1.43	48.45	2.58
Diesel car	2.19	2.19	0.38	0.38	47.3	1.43	49.87	4.00
Public transport	0.22	0.69	0.00	0.00			0.22	0.69

4.4. The reference equilibrium

Table 4 summarises demand and price information in the reference equilibrium. The following observations stand out from these figures. First, as previously suggested, under current policies variable taxes are smaller for diesel than for gasoline cars, whereas the opposite holds for fixed taxes. Note that the ownership tax differences are not just due to tax differences per se, they also reflect differences in the characteristics of the average diesel and gasoline car (e.g., power, size, etc.). However, this only accounts for part of the observed difference: diesel cars with otherwise similar characteristics are subject to higher fixed taxes than gasoline cars. Second, in the peak period variable car taxes are substantially below marginal external costs. For example, gasoline car use is taxed at 0.08 euro per passenger kilometre in the peak period (Table 4), whereas the direct marginal external cost amounts to 0.485 per passenger kilometre (see Table 3). Third, while variable taxes in Belgium are higher for gasoline than for diesel cars, the opposite holds for marginal external costs. Fourth, the current variable tax instruments do not allow a differentiation of variable taxes according to the time of travel, while the marginal external costs differ substantially between peak and off-peak. Finally, public transport operating costs are heavily subsidised.

The current tax structure has obvious implications for the structure of the car stock and for car use, see again Table 4. The share of diesel cars in the total car stock is among the highest in Europe (Mayeres and Proost (2001)): in 2000 it amounted to approximately 40% and was still rising. Moreover, the relatively low user taxes induce diesel cars to be chosen

especially by high demand users. The average annual distance covered by a diesel car is more than 50% higher than for the typical gasoline car. Also note the relevance of taking into account non car owners, especially when incorporating public transport availability. Non-ownership amounts to almost 20%; the share of non-owners in overall public transport demand is more than 40%.

Table 4: The reference equilibrium

		Reference equilibrium
Variable tax (euro/pkm)		
Public	Peak	-0.06
	Off-peak	-0.07
Gasoline car	Peak & off-peak	0.08
Diesel car	Peak & off-peak	0.06
Fixed tax (euro/car/year)		
	Gasoline	640
	Diesel	986
Ownership probabilities		
	No car	19%
	Gasoline car	48%
	Diesel car	33%
Car stock (million cars)		4.68
Conditional annual mileage (pkm/year/household)		
No car	Public	3674
	Gasoline car owner	2503
Diesel car owner	Car	20872
	Public	2503
	Car	32079
Total transport demand (10^9 pkm/year)		
Public	Peak	5.91
	Off-peak	5.64
Car	Peak	36.40
	Off-peak	50.86
Average speed (km/h)		
	Peak	43
	Off-peak	98

5. Optimal taxation of car ownership, car use and public transport in Belgium: numerical results

In this section we turn to the optimal tax results obtained with the numerical model. We first present the various policies studied (subsection 5.1), and then discuss the detailed results for the different scenarios (subsection 5.2). Policy implications are summarised in subsection 5.3.

5.1. The scenarios analyzed

As suggested before, we consider a richer range of policies than in the theoretical sections. An overview of the scenarios analysed is presented in Table 5. Scenarios 2 and 3 closely resemble the tax problems studied in theory in Section 2; the others serve to approximate various other policy options. To summarise, note that in Scenarios 1 and 2 it is assumed that all available taxes (fixed car taxes, variable car taxes and public transport prices in the different periods) can be determined optimally; Scenario 2 assumes a budgetary neutral operation, whereas Scenario 1 does not constrain government revenues but assigns an equal weight to consumer welfare and tax revenues. To get insight into the role fixed car taxes can play if for political or distributive reasons governments refrain from strongly adjusting variable car taxes, Scenario 3 looks at the case where variable car taxes are exogenously fixed at their current levels, and it determines public transport and fixed car taxes optimally. Scenario 4 asks what can be optimally done on the basis of currently used tax instruments: it allows using all instruments but assumes that variable taxes cannot be differentiated according to peak and off peak periods; this is currently the case in Belgium, where fuel taxes are the main variable tax instrument. Finally, Scenarios 5 and 6 approximate for policies that are based on time differentiated kilometre taxes as the main variable tax instrument. To test for the potential welfare improvements that are possible when variable taxes cannot be differentiated according to fuel type, these scenarios answer this question for the case of uniform (Scenario 5) and differentiated (Scenario 6) fixed car taxes. The differences between these two scenarios will provide information on the role of differentiated fixed taxes when variable taxes are not differentiated according to fuel type.

Table 5: Scenario assumptions

	Tax instruments			
	Variable car taxes	Variable taxes public transport	Fixed car taxes	Additional constraints
Scenario 1	Optimal	Optimal	Optimal	None
Scenario 2	Optimal	Optimal	Optimal	Transport tax revenue unchanged w.r.t. reference equilibrium
Scenario 3	Reference level	Optimal	Optimal	None
Scenario 4	Optimal – No difference between peak and off-peak	Optimal – No difference between peak and off-peak	Optimal	None
Scenario 5	Optimal – No difference between gasoline and diesel	Optimal	Optimal – No difference between gasoline and diesel	None
Scenario 6	Optimal – No difference between gasoline and diesel	Optimal	Optimal	None

5.2. Empirical results

The results of the six optimization scenarios in terms of optimal taxes, demand structure and welfare effects are summarised in Tables 6, 7 and 8, respectively. Note that the objective function was discussed in Section 3.4. To facilitate the interpretation, in the exercises based on an exogenously imposed weight of government tax revenues, it was assumed that ψ equals unity (see (36)).

Consider Scenario 1. First and most importantly, it follows that the current tax structure on diesel and gasoline car ownership and car use cannot be justified in terms of external costs and budgetary considerations. In the current tax structure, diesel taxes fall short of gasoline taxes (0.06 versus 0.08) but diesel cars are taxed much heavier than gasoline cars (986 euro versus 640 euro). On the contrary, the optimal variable taxes on diesel slightly exceed (by 0.01 euro) those on gasoline to reflect the higher pollution costs associated with the use of diesel. Moreover, the current differences in annual vehicle taxation are unwarranted as well: the optimal fixed taxes hardly differ between diesel and gasoline cars. They are

drastically lower than in the reference, amounting to some 400 euro. Second, consistent with earlier literature (Mayeres and Proost (1997), De Borger and Proost (2001)), the unrestricted optimal tax structure implies higher variable car taxes on both gasoline and diesel car use in the peak period to capture the high congestion externalities in that period. Peak period variable taxes are as high as 0.20 euro per kilometre. Third, public transport operating subsidies in the reference case are replaced by optimal taxes that slightly exceed the full marginal external costs; this is due to correct pricing of the competing car modes.

The optimal tax structure has obviously important effects on the composition of the car stock and the transport demand structure. Table 7 suggests that it implies an increase in the car stock by some 0.3% but, not surprisingly, the share of diesel cars in the stock declines substantially: the number of diesel cars goes down by some 8.2%. Car use in the peak period declines by 18.5%, while off-peak car use increases substantially, by some 21.5%. In the peak period this results in a substantial increase of average speed. In both periods, the share of diesel cars in the production of car kilometres declines. Public transport use falls in both periods. The decline is largest for the off-peak period. The higher public transport fares also reduce demand by people not owning a car (a decline by some 13.7%), a potentially undesirable effect from a distributive point of view.

Table 8 summarises the effects of the optimal tax structure on the different components of the objective function. First, the tax increase implies that the utility component U increases slightly, although both non-car owners and diesel car owners are worse off. Second, the utility gain is reinforced by the higher tax revenues and the reduction in pollution and accident risks. The extra tax revenues provide the main contribution to the increase in social welfare.

Table 6: Optimal fixed and variable taxes under the various scenarios

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Variable tax (euro/pkm)							
Peak public	-0.06	0.004	0.027	-0.041	-0.007	0.006	0.004
Off-peak public	-0.07	0.009	0.007	0.010	-0.007	0.011	0.009
Peak gasoline car	0.08	0.20	0.21	0.08	0.09	0.21	0.21
Off-peak gasoline car	0.08	0.04	0.04	0.08	0.09	0.04	0.04
Peak diesel car	0.06	0.21	0.22	0.06	0.11	0.21	0.21
Off-peak diesel car	0.06	0.05	0.06	0.06	0.11	0.04	0.04
Full marginal external costs^a (euro/pkm)							
Peak public	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Off-peak public	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Peak gasoline car	0.23 (0.48)	0.185 (0.20)	0.186 (0.20)	0.229 (0.20)	0.230 (0.42)	0.185 (0.20)	0.185 (0.20)
Off-peak gasoline car	0.03 (0.03)	0.035 (0.03)	0.034 (0.03)	0.028 (0.03)	0.026 (0.02)	0.035 (0.03)	0.035 (0.03)
Peak diesel car	0.25 (0.50)	0.199 (0.21)	0.200 (0.21)	0.243 (0.21)	0.244 (0.44)	0.199 (0.21)	0.199 (0.21)
Off-peak diesel car	0.04 (0.04)	0.049 (0.05)	0.049 (0.05)	0.042 (0.04)	0.040 (0.04)	0.049 (0.05)	0.049 (0.05)
Fixed tax (euro/car/year)							
Gasoline car	640	408	142	858	848	357	299
Diesel car	986	421	-260	1949	905	357	606
Generalised price (euro/pkm)							
Peak public	0.24	0.30	0.32	0.26	0.29	0.30	0.30
Off-peak public	0.18	0.26	0.26	0.26	0.25	0.26	0.26
Peak gasoline car	0.33	0.38	0.39	0.32	0.32	0.40	0.39
Off-peak gasoline car	0.21	0.17	0.17	0.21	0.21	0.18	0.17
Peak diesel car	0.32	0.41	0.42	0.31	0.35	0.40	0.40
Off-peak diesel car	0.20	0.19	0.20	0.20	0.25	0.18	0.18
Probabilities							
No car	19%	18.7%	18.5%	19.4%	19.3%	18.7%	18.7%
Gasoline car	48%	51.1%	50.3%	52.6%	52.0%	49.3%	51.2%
Diesel car	33%	30.2%	31.3%	28.1%	28.7%	31.9%	30.1%
Car stock	millions	Percentage change w.r.t. reference equilibrium					
	4.678	+0.3%	+0.7%	-0.4%	-0.4%	+0.3%	+0.3%

Note: for a description of the scenarios, see Table 5.

^a The marginal external cost figures are the calculated full external costs; the figures between brackets refer to the direct marginal external costs.

Table 7: The impact of the scenarios on travel demand and average car speed

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Conditional annual mileage	pkm/year /household	Percentage change w.r.t. reference equilibrium					
<u>No car public</u>	3674	-13.7%	-15.3%	-9.8%	-11.4%	-14.1%	-13.8%
<u>Gasoline car owners public car</u>	2503 20872	-40.1% +13.1%	-43.6% +13.8%	-30.0% +2.0%	-35.1% +2.3%	-38.9% +9.3%	-38.9% +10.4%
<u>Diesel car owners public car</u>	2503 32079	-33.2% -1.7%	-34.9% -5.6%	-31.0% +0.5%	-26.3% -11.8%	-34.8% +0.6%	-35.0% +1.3%
Traffic	10 ⁹ pkm/year	Percentage change w.r.t. reference equilibrium					
Public	11.55	-31.6%	-34.2%	-24.9%	-26.6%	-31.5%	-31.5%
Peak public	5.91	-20.5%	-27.4%	-9.2%	-21.6%	-20.5%	-20.5%
Off-peak public	5.64	-43.2%	-41.3%	-41.4%	-31.8%	-43.1%	-43.1%
Car	87.26	+4.8%	+4.0%	-1.7%	-6.7%	+4.7%	+4.8%
Peak car	36.40	-18.5%	-18.3%	-1.2%	-2.8%	-18.6%	-18.6%
Off-peak car	50.86	+21.5%	+19.9%	+2.0%	-9.4%	+21.3%	+21.4%
Total	98.81	+0.5%	-0.5%	-4.4%	-9.0%	+0.4%	+0.5%
Average car speed (km/h)							
Peak	43	62.7	62.4	44.2	45.9	62.8	62.7
Off-peak	98	93.9	94.2	98.3	99.5	93.9	93.9

Note: for a description of the scenarios, see Table 5.

Table 8: Welfare effects of optimal taxes

	REF	Scenarios					
		1	2	3	4	5	6
Social welfare (10 ⁶ euro/year)		Change w.r.t. reference					
N.U	1142687	302	1648	-2401	-2443	294	305
Change in tax revenue* ψ	0	1386	0	2497	2527	1414	1389
Change in external costs	0	34	46	234	229	-12	19
Total	1142687	1721	1693	330	313	1696	1713
Relative performance w.r.t. Scenario 1							
		100%	98.4%	13.9%	18.2%	98.5%	99.5%
Conditional utility (10 ³ euro/household/year)							
no car	230.22	229.98	229.94	230.02	230.02	229.97	229.97
gasoline car	262.53	262.91	263.23	262.22	262.20	262.77	262.92
diesel car	260.99	260.78	261.31	259.79	259.79	261.01	260.77

Note: for a description of the scenarios, see Table 5

In Scenario 2 we consider the optimal tax structure for the case where the government aims at correctly pricing externalities, but where the operation is assumed to be budgetary neutral: revenues are fixed at their reference level. The results for this scenario, which is the numerical equivalent to the theoretical model of Section 2.2, provide information on optimal adjustments to the current tax structure without generating extra revenues; this is often considered desirable for purposes of acceptability. The results of Scenario 2 suggest keeping the variable car taxes at approximately the same level as in Scenario 1, but at the same time drastically reducing the fixed tax levels (see Table 6). Consistent with the theory, variable car taxes exceed marginal external costs, the difference being largest for diesel car users. The higher variable taxes allow the fixed taxes to be set at very low levels; for diesel cars a subsidy is optimal. Differences in fixed tax levels are driven by deviations in variable taxes from the marginal external costs and differences in conditional public transport demand (see Section 2.2). As diesel car use is taxed higher relative to marginal external cost, this is compensated by a somewhat higher fixed tax on gasoline cars. It amounts to some 140 euro per year, whereas for diesel car owners we actually observe a subsidy on ownership. Public transport subsidies are eliminated, which is consistent with the theory of Section 2.2.

The conclusion for Scenario 2 is clear: at current levels of tax revenues, the existing tax structure implies too much emphasis on fixed taxes and imposes incorrectly low variable car taxes in the peak period. In fact, given the low level of optimal fixed taxes in Scenario 2 they can probably simply be abolished at a relatively small welfare cost. Off-peak car taxes are approximately correct. The currently existing subsidies to public transport are too high.

The described optimal tax policy of Scenario 2 increases the car stock, and encourages some shift of diesel cars to gasoline cars in the stock. Total car transport increases by 4% and there is a shift from peak to off-peak transport. The demand for public transport falls slightly more than in Scenario 1. The welfare gain amounts to approximately 98.4% of that in Scenario 1. The lower level of taxation raises the utility component, but there is obviously no extra tax revenue. The external cost savings are larger than in Scenario 1 because there is a fall instead of a small increase in total transport demand.

Scenario 3 looks at the kind of instrument restriction considered in Section 2.3. In this scenario we simply assume that public opposition forces variable car taxes to remain at their reference levels, so that fixed car taxes and public transport fares are the main devices for correcting all externalities. As shown in Table 6, this induces large increases in fixed taxes. Moreover, given the substantial under-taxation of diesel use in the reference situation and the higher external costs associated with diesel use, the resulting fixed tax on diesel cars is more than twice as high as for gasoline cars, almost 1950 euro for diesel compared to 860 for gasoline cars. Public transport subsidies are maintained in the peak period, though they are smaller than in the reference case. In the off-peak, public transport subsidies are replaced by taxes, since they have no major role to play in correcting for congestion. The result of this pricing scheme is that the total car stock is reduced (Table 7), and there is a large shift from diesel to gasoline cars. Table 8 suggests that the policy analyzed in Scenario 3 implies that substantial welfare gains can be realised by optimally differentiating fixed car taxes. Unfortunately, of course, as fixed taxes are not suited very well to tackle congestion (yielding too much car traffic in the peak period and too little car traffic in the off-peak period), the figures in Table 8 suggest that Scenario 3 is much less efficient than Scenario 1: it only yields 14% of the potential welfare gain.

The aim of Scenario 4 is to see what can be done with the set of tax instruments currently in use. To mimick the idea of combining fixed car taxes with the use of fuel taxes as the main variable tax instrument on car use, we assume all tax instruments are available, but variable taxes are restricted to be equal for peak and off-peak travel. Table 6 shows that the resulting optimal variable taxes are in between the full marginal external costs in the peak and the off-peak period. More importantly, because the variable car taxes in the peak are too low relative to the optimum, fixed car taxes are higher than in Scenario 1. They do not differ substantially between fuel types, being again somewhat higher for diesel cars; they amount to 850-900 euros per year. This corresponds to an increase in the tax on gasoline cars with

respect to the reference; the tax on diesel cars slightly declines. Public transport is almost priced at marginal operating costs, very small subsidies remain.

Summarizing Scenario 4, optimising the currently used set of tax instruments would suggest reducing public transport subsidies, raising fuel taxes on car use (slightly for gasoline, more substantially for diesel), and approximately equalizing fixed car taxes at a level between the current levels for gasoline and diesel cars.

The higher fixed taxes in this scenario lead to a reduction in the car stock and there is a shift towards more gasoline cars and more gasoline car km. However, the uniform variable taxes lead to a reduction in both peak and off-peak car transport. They are therefore much less appropriate to address congestion. Compared to the optimum peak car transport is too high and off-peak car transport is too low. As a result only 18.2% of the maximum welfare gain can be obtained by restricting the variable taxes to be uniform across periods.

Scenario 5 and 6 finally imitate the use of optimal time-differentiated kilometre taxes by assuming that variable car taxes are restricted to be uniform across fuel types. In Scenario 5 it is further assumed that fixed car taxes are uniform; this is not the case in Scenario 6. Results for Scenario 5 are as follows: fixed car taxes are drastically reduced compared to the reference situation. Due to the higher tax revenues on variable taxes, they are even lower than in Scenario 1. Since air pollution costs are only a minor component of the social welfare function and the kilometre taxes are time-differentiated, this scenario does not perform much worse than Scenario 1: it achieves 98.5% of the welfare gain.

When variable taxes are restricted to be uniform across fuel types, but fixed taxes are not – as in Scenario 6 – the full optimum can be approximated very closely by setting a fixed tax on diesel cars that is twice that on gasoline cars. Using this strategy one realises 99.5% of the maximum welfare gain. In other words, the use of time-differentiated kilometre taxes combined with fixed tax differentiation on car types comes very close to Scenario 1.

5.3. Policy implications

It is instructive to summarise some implications of the optimal tax results. In view of the topic of the paper, we emphasise the findings with respect to optimal fixed taxes and the role of public transport.

- (i) Assuming that the government has perfect tax instruments (Scenario 1), we found that optimal fixed car taxes fall from their current levels to about 400

euro per year; they do not differ notably between car types. Public transport subsidies would decline substantially; peak car taxes would rise to capture congestion costs.

- (ii) If the government has all instruments but, for reasons of acceptability of its policies, restricts tax revenues to currently observed tax revenues (Scenario 2), then we found fixed car taxes to be very low (140 euro for gasoline cars, negative for diesel cars); in fact, in view of administrative costs of tax collection, it might in this case be optimal to eliminate fixed car taxes altogether. Variable car taxes would exceed the respective marginal external costs; public transport fares would exceed marginal operating costs.
- (iii) If the government used the set of instruments it currently employs but chooses the tax levels optimally (Scenario 4), then it would raise the fixed car tax on diesel by some 200 euro, while slightly reducing it for gasoline cars. Public transport would be subsidised, although at lower rates than in the reference situation.
- (iv) If the government is unwilling to adjust variable car taxes (Scenario 3), then very large increases in fixed taxes on diesel cars are required: the tax on diesel cars approximately doubles, that on gasoline cars rises by some 30%.
- (v) Finally, despite limited welfare losses of kilometre taxes, the implications of kilometre taxes (Scenario 6) as opposed to perfect tax instruments for the levels of the fixed taxes are substantial. Whereas perfect variable tax instruments (and hence differentiation between fuel types) yielded fixed taxes that hardly differed according to fuel type, this is not the case if kilometre taxes are used. The inability to differentiate variable taxes between diesel and gasoline implies that, although both fixed taxes decline relative to the reference case, diesel taxes (606 euro) are approximately twice this on gasoline cars (299 euro). In other words, the use of kilometre taxes instead of full blown road pricing has large implications for the level of optimal fixed taxes, an observation not previously made in the literature.

6. Revenue-neutral marginal policy reforms

As illustrated by the exercises reported in the previous section, full adjustment to optimal taxes often result in large changes from current values of the policy instruments. Policy makers may therefore be reluctant to implement the recommendations of optimal tax studies. In this section, we therefore also use the numerical model to perform a series of budgetary neutral marginal tax reform exercises, starting from the reference equilibrium. We focus on very small marginal tax changes: in each case, it is assumed that one tax is increased just enough to raise 1 additional euro of tax revenue, and that this is compensated by a reduction in one other tax. This type of analysis has been often used in the literature (see, e.g., Ahmad and Stern (1984), Ballard and Medema (1993), and Mayeres (2000)). It is especially useful to identify which policy instrument yields the highest welfare gain when used to generate extra tax revenue, and which of the available instruments is the most appropriate ‘recycling’ instrument.

In the remainder of this section, we review the tax reforms implemented (subsection 6.1), discuss the numerical results (subsection 6.2) and summarise the policy implications of our findings (subsection 6.3).

6.1. The policy packages considered

The policy packages consist of a combination of two of the following instruments¹²:

- a. Fuel tax: the variable tax on gasoline or diesel car use is varied by the same amount in the peak and the off-peak period. Since fuel efficiency is assumed not to differ between the peak and the off-peak period and the fuel taxes are currently the same in the two periods, this indeed corresponds to a change in the fuel tax.
- b. Road pricing: the variable tax on gasoline and diesel cars is increased in the peak period. This means that, on top of the existing fuel taxes, car users pay a charge that is

¹² Note that the reform exercise of this section bears quite some similarity to Mayeres (2000) and Mayeres and Proost (2001). Differences are that we use a different set of transport tax instruments, focusing on the trade-offs between fixed and variable taxation. On the other hand, our partial equilibrium approach implies that we restrict ourselves to transport tax instruments, whereas the studies referred to above also considered general tax instruments, such as the labour income tax and social security transfers.

equal for the two car types. If variable taxes are used to recycle tax revenues, the variable tax on off-peak transport is reduced.

- c. Fixed taxes: the fixed annual tax on gasoline or diesel cars is altered.
- d. Public transport subsidies: public transport subsidies are adjusted in the peak or the off-peak period.

As the reforms are budgetary neutral, we can measure the change in social welfare as the change in

$$SW = N.U - E \quad (37)$$

with respect to the initial equilibrium. The change in the final term captures the change in expected air pollution and accident costs with respect to the reference situation. In the calculation of changes in U it is obviously taken into account that the time needed per car km is affected by the car traffic flow that follows from the policy change¹³.

6.2. Numerical results

The results are given in Table 9; it is divided in three parts. The upper part of the table presents the full marginal welfare impact of the policy reforms, while the middle and the bottom part isolate two components that contribute to this change: the marginal benefit of the change in congestion and of the change in air pollution and accidents. To see the interpretation, consider the case where road pricing is used to tackle external costs and that budgetary neutrality is guaranteed by a reduction in the fuel tax on gasoline. The figure 0.71 in the first column on the second row in the upper part of the table then means that, if road pricing is used to generate 1 extra euro of revenue, and if simultaneously gasoline taxes are reduced to keep the initial budget fixed, this joint operation generates a net welfare gain of 0.71 euro. The middle and bottom parts of the table further indicate that this policy package yields a marginal benefit of 0.59 due to the reduction in congestion, whereas an extra benefit of 0.05 euro is due to the reduction in pollution and accident costs.

¹³ In a previous version of the paper, we also calculated the welfare effects of marginal tax reforms on the assumption that externalities did not matter, so that revenue raising was the government's only objective. It was found that reducing public transport subsidies and raising fixed car taxes were the most efficient revenue raising instruments. Variable car taxes were the most efficient recycling instruments. Results are available on request.

With this interpretation in mind, a first observation that follows from Table 9 is that peak road pricing is the policy measure generating the highest marginal welfare gain for a given revenue recycling strategy. This can be seen by horizontal comparison of the figures in the upper part of the table. Road pricing leads to a positive welfare effect for all recycling instruments considered in Table 9. Since it introduces a price differentiation between the peak and the off-peak period it is the most efficient instrument to tackle congestion, which is the dominant externality in the model. We found (not shown in the table) that peak road pricing generated a marginal congestion benefit of 0.84 euro per euro of government revenue, before taking into account the way in which the revenue is used. As can be seen from the middle part of Table 9, some revenue recycling instruments even reinforce this reduction in congestion. This is the case for higher public transport subsidies (marginal congestion benefit equal to 1.1) since they encourage the switch from car to public transport. A lower fixed tax on gasoline cars also generates additional congestion benefits, because it encourages a switch from diesel cars to gasoline cars with a lower corresponding conditional mileage. The other revenue recycling instruments reduce the beneficial effect of peak road pricing on congestion.

Peak road pricing also leads to less air pollution and accidents, though the net effect on these externalities will vary according to the revenue recycling strategy that is used. Given the high air pollution damage caused by diesel cars, reducing taxes on diesel cars will lead to a net increase in air pollution costs. Reducing the variable car taxes on off-peak transport will also lead to a net increase in air pollution costs, given the relative magnitude of off-peak car transport and its price elasticity.

Table 9: The marginal welfare impacts of revenue-neutral transport policy packages in the presence of congestion, air pollution and accidents (euro per euro of government revenue)

Transport instrument →	Peak road pricing	Higher fuel tax diesel	Higher fixed tax diesel	Higher fixed tax gasoline
Budget neutrality ensured by ↓				
Marginal welfare impact				
Lower off-peak variable car tax	1.01	0.80	0.64	0.37
Lower fuel tax gasoline	0.71	0.50	0.34	0.06
Lower fuel tax diesel	0.21		-0.17	-0.44
Lower fixed tax gasoline	0.65	0.44	0.27	
Lower fixed tax diesel	0.38	0.17		-0.27
Higher peak public tp. subsidies	0.49	0.28	0.12	-0.16
Higher off-peak public tp. subsidies	0.19	-0.02	-0.19	-0.46
Marginal benefit of the change in congestion				
Lower off-peak variable car tax	0.81	0.72	0.24	-0.10
Lower fuel tax gasoline	0.59	0.50	0.02	-0.32
Lower fuel tax diesel	0.10		-0.48	-0.82
Lower fixed tax gasoline	0.92	0.82	0.34	
Lower fixed tax diesel	0.57	0.48		-0.34
Higher peak public tp. subsidies	1.10	1.00	0.53	0.19
Higher off-peak public tp. subsidies	0.91	0.82	0.34	0.00
Marginal benefit of the change in air pollution and accidents				
Lower off-peak variable car tax	-0.12	0.09	-0.03	-0.18
Lower fuel tax gasoline	0.05	0.25	0.13	-0.01
Lower fuel tax diesel	-0.20		-0.12	-0.26
Lower fixed tax gasoline	0.06	0.26	0.14	
Lower fixed tax diesel	-0.08	0.12		-0.14
Higher peak public tp. subsidies	0.02	0.22	0.10	-0.04
Higher off-peak public tp. subsidies	0.01	0.21	0.09	-0.06

Interestingly, the second most efficient instrument (for a given revenue recycling strategy) is the fuel tax on diesel. In all cases except one it leads to a welfare gain. In view of our focus on the role of fixed taxes, note that financing the fuel tax increase by a reduction in the fixed tax on diesel cars (a standard argument in the popular press to move from fixed to variable taxation on cars) is indeed welfare improving. However, also note that reducing off peak variable taxes is a more efficient recycling instrument: the welfare impact amounts to 0.5 in this case, versus 0.17 in the case of a lower fixed diesel tax. Policy combinations containing higher diesel fuel taxes also reduce the traffic flow, but in a blunt way: they do not make a distinction between peak and off-peak. Therefore, the marginal benefit of a reduction in congestion is lower than in the case of peak road pricing. The higher fuel tax on diesel mainly

performs well because it reduces the emission damages from diesel cars for all revenue recycling strategies considered in Table 9.

In some, but not all, cases, raising fixed car taxes also leads to a net welfare gain. Since diesel cars are more polluting than gasoline cars, higher fixed taxes on diesel cars perform better than an increase in the fixed taxes on gasoline cars. Even then, however, note that it is important to carefully consider recycling instruments. Higher taxes on diesel cars are welfare improving only if recycled through lower off peak variable car taxes or lower taxes on gasoline; recycling via lower taxes on diesel is welfare reducing. For almost all revenue recycling strategies, higher fixed taxes on diesel cars have a positive impact on congestion since they encourage a switch to gasoline cars with lower conditional transport demand. In contrast, a higher fixed tax on gasoline cars mostly leads to more congestion, unless it is accompanied by higher public transport subsidies.

Vertical comparison of the recycling instruments for an increase in a given policy instrument shows that it appears always best to reduce the variable taxes on off-peak car transport. A reduction in fuel taxes performs worse, partly because it increases the congestion level. Moreover, a reduction in the fuel tax on diesel is worse than for gasoline, because diesel cars lead to higher air pollution costs and demand for diesel car transport is more price responsive.

The marginal welfare gains with lower fixed car taxes are also smaller than with lower variable car taxes in the off-peak. This is the case because fixed taxes are relatively efficient tax instruments for raising revenue, so that less can be gained by reducing them. Moreover, a lower fixed tax on diesel cars also increases the level of the three transport externalities. The opposite is true for a lower fixed tax on gasoline cars, which explains why this instrument performs better as a recycling instrument than the fixed tax on diesel cars.

Finally, increasing public transport subsidies in some cases also is a recycling instrument with positive welfare effects. The reason is obviously that higher subsidies reduce transport externalities. This is especially true for public transport subsidies in the peak period since they have the largest impact on the congestion level.

6.3. Policy implications

Of course, the exercises reported in this section are limited because they are restricted to changing only the existing tax instruments on car use and ownership. Still, the results in Table 9 lead to two interesting general conclusions.

- (i) Marginal shifts from gasoline to diesel taxation, both for variable and fixed taxes, are welfare improving. Both higher fixed and variable diesel taxes, financed by especially lower fixed taxes on gasoline cars, are policy packages with substantial welfare benefits. This confirms the results of Mayeres and Proost (2001).

- (ii) Somewhat surprisingly, a switch from fixed to variable taxes has ambiguous effects. For diesel cars, it is welfare improving to marginally reduce the fixed tax and to compensate the resulting revenue loss by a higher fuel tax. For gasoline cars, however, the impact of such a shift on the externalities is such that this recommendation does not yield beneficial welfare effects.

7. Conclusions and extensions

In this paper we presented a simple discrete/continuous choice model to study optimal two-part tariffs in the presence of externalities. The theoretical analysis focused on the specific role of variable and fixed taxes on vehicles to correct for externalities; the model assumed owners and non owners of cars all had access to public transport options, and it looked at constraints on the variable tax instruments. An empirical application of a numerical and extended version of the model to the optimal taxation of cars in Belgium yielded the following results. First, the current differences in tax treatment between diesel and gasoline cars and their use do not appear to be justified on the basis of the externalities they generate nor on the basis of budgetary considerations. Efficient pricing requires substantial increases in the relative user tax on diesel cars as compared to gasoline cars; optimal fixed taxes are substantially below current levels and only marginally differ between car fuel types. Moreover, efficient pricing involves a substantial increase in variable car taxes in the peak period to correct for externalities. Public transport subsidies on operating costs would be replaced by variable taxes. Large differences in fixed car taxes do result if for political or technical reasons variable taxes cannot be optimally adjusted. The same is true if the government uses a system of kilometre taxes that does not allow fuel differentiation as the main variable tax instrument.

In a series of marginal tax reform exercises, we found that marginal shifts from gasoline to diesel taxation, both for variable and fixed taxes, are welfare improving. Both higher fixed and variable diesel taxes, financed by especially lower fixed taxes on gasoline cars, are policy packages with substantial welfare benefits. However, a switch from fixed to variable taxes has ambiguous effects. For diesel cars, it is welfare improving to marginally reduce the fixed tax and to compensate the resulting revenue loss by a higher fuel tax. For gasoline cars, however, the impact of such a shift on the externalities is such that this recommendation does not yield beneficial welfare effects.

It is clear that the analysis of this paper can be improved and extended. For example, it does not yet consider the equity issues associated with the imposition of two-part tariffs. Since equity issues cannot be ignored in transport policy reforms, this issue will be taken up in a follow-up paper.

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Appendix 1: derivation of optimal tax rules

The government's problem is to optimally select both the three variable prices p_g, p_d, p_b and the two fixed car taxes F_g, F_d so as to maximise

$$N\mu \ln \left\{ \exp\left(\frac{V_g(p_g, p_b, y - F_g, E)}{\mu}\right) + \exp\left(\frac{V_d(p_d, p_b, y - F_d, E)}{\mu}\right) + \exp\left(\frac{V_o(p_b, y, E)}{\mu}\right) \right\}$$

subject to the budget restriction

$$N \left\{ [(p_g - c_g)x_c^g + F_g] \pi_g + [(p_d - c_d)x_c^d + F_d] \pi_d + [(p_b - c_b)(\pi_g x_b^g + \pi_d x_b^d + \pi_o x_b^o)] \right\} = G$$

First consider the first-order condition with respect to p_g . Using similar procedures as in De Borger (2001, appendix 1) it can be written as

$$\begin{aligned} & (p_g - c_g - \theta_g) \left(\pi_g \frac{\partial x_c^g}{\partial p_g} + x_c^g \frac{\partial \pi_g}{\partial p_g} \right) + (p_d - c_d - \theta_d) \left(x_c^d \frac{\partial \pi_d}{\partial p_g} \right) \\ & + (p_b - c_b - \theta_b) \left[\pi_g \frac{\partial x_b^g}{\partial p_g} + x_b^g \frac{\partial \pi_g}{\partial p_g} + x_b^d \frac{\partial \pi_d}{\partial p_g} - x_b^o \left(\frac{\partial \pi_g}{\partial p_g} + \frac{\partial \pi_d}{\partial p_g} \right) \right] \\ & + F_g \frac{\partial \pi_g}{\partial p_g} + F_d \frac{\partial \pi_d}{\partial p_g} = \left(\frac{m_g - \lambda}{\lambda} \right) \pi_g x_c^g \end{aligned} \quad (A.1)$$

where λ is the multiplier associated with the constraint, $m_g = \frac{\partial V_g}{\partial y}$ is the marginal utility of income for owners of a gasoline car, and the θ_i ($i=g,d,b$) reflect the full marginal external cost of an increase in demand for kilometres by a gasoline car, a diesel car or public transport, taking account of potential feedbacks of the externality on demand. Differentiating the definition of the externality $E = f(X_c^g, X_c^d, X_b)$ and taking into account the dependency of all conditional demands and probabilities on E, they can be written as follows:

$$\theta_g = \{K\} \frac{1}{1-\rho} \frac{\partial f(\cdot)}{\partial X_c^g}$$

$$\theta_d = \{K\} \frac{1}{1-\rho} \frac{\partial f(\cdot)}{\partial X_c^d}$$

$$\theta_b = \{K\} \frac{1}{1-\rho} \frac{\partial f(\cdot)}{\partial X_b}$$

where

$$\begin{aligned}
K &= \pi_g \frac{\partial V_g}{\partial E} + \pi_d \frac{\partial V_d}{\partial E} + \pi_o \frac{\partial V_o}{\partial E} \\
&+ \lambda \left\{ (p_g - c_g) \left(\pi_g \frac{\partial x_c^g}{\partial E} + x_c^g \frac{\partial \pi_g}{\partial E} \right) + (p_d - c_d) \left(\pi_d \frac{\partial x_c^d}{\partial E} + x_c^d \frac{\partial \pi_d}{\partial E} \right) + F_g \frac{\partial \pi_g}{\partial E} + F_d \frac{\partial \pi_d}{\partial E} \right\} \\
&+ \lambda \left\{ (p_b - c_b) \left[\pi_g \frac{\partial x_b^g}{\partial E} + x_b^g \frac{\partial \pi_g}{\partial E} + \pi_d \frac{\partial x_b^d}{\partial E} + x_b^d \frac{\partial \pi_d}{\partial E} + \pi_o \frac{\partial x_b^o}{\partial E} - x_b^o \left(\frac{\partial \pi_g}{\partial E} + \frac{\partial \pi_d}{\partial E} \right) \right] \right\}
\end{aligned}$$

is the full welfare effect of an increase in E (i.e., the direct utility impact plus all budgetary implications evaluated at the shadow cost of the budget constraint), and ρ is the feedback effect defined as

$$\begin{aligned}
\rho &= \frac{\partial f(\cdot)}{\partial X_c^g} \left(\pi_g \frac{\partial x_c^g}{\partial E} + x_c^g \frac{\partial \pi_g}{\partial E} \right) + \frac{\partial f(\cdot)}{\partial X_c^d} \left(\pi_d \frac{\partial x_c^d}{\partial E} + x_c^d \frac{\partial \pi_d}{\partial E} \right) \\
&+ \frac{\partial f(\cdot)}{\partial X_b} \left(\pi_g \frac{\partial x_b^g}{\partial E} + x_b^g \frac{\partial \pi_g}{\partial E} + \pi_d \frac{\partial x_b^d}{\partial E} + x_b^d \frac{\partial \pi_d}{\partial E} + \pi_o \frac{\partial x_b^o}{\partial E} + x_b^o \frac{\partial \pi_o}{\partial E} \right)
\end{aligned}$$

The feedback term measures the indirect impact of an increase in E on the level of the externality itself via the conditional demands and ownership probabilities. It will be negative whenever the externality reduces demand. Congestion and accident risks are typical externalities that generate such feedbacks. For example, an increase in traffic raises congestion. This in turn reduces the conditional demand for car use as well as the desirability of owning a car. The demand-reducing effect of the externality itself mitigates the increase in the externality after an initial increase in X . Pollution, on the other hand, may well be an example of an externality without feedback effects. The effect of the feedback is that it may substantially dampen the effect of price changes. Holding the externality E constant, an increase in the price of diesel in principle affects the demand for both diesel and gasoline, and therefore, it affects the externality level. But since the externality itself in turn affects demands the overall price impact is adjusted.

Analogously, the first-order condition for the fixed annual fee on gasoline cars can be written as

$$\begin{aligned}
&(p_g - c_g - \theta_g) \left(\pi_g \frac{\partial x_c^g}{\partial F_g} + x_c^g \frac{\partial \pi_g}{\partial F_g} \right) + (p_d - c_d - \theta_d) \left(x_c^d \frac{\partial \pi_d}{\partial F_g} \right) \\
&+ (p_b - c_b - \theta_b) \left[\pi_g \frac{\partial x_b^g}{\partial F_g} + x_b^g \frac{\partial \pi_g}{\partial F_g} + x_b^d \frac{\partial \pi_d}{\partial F_g} - x_b^o \left(\frac{\partial \pi_g}{\partial F_g} + \frac{\partial \pi_d}{\partial F_g} \right) \right] \\
&+ F_g \frac{\partial \pi_g}{\partial F_g} + F_d \frac{\partial \pi_d}{\partial F_g} = \left(\frac{m_g - \lambda}{\lambda} \right) \pi_g
\end{aligned} \tag{A.2}$$

The first order conditions with respect to the variable and fixed diesel taxes are derived in a completely similar fashion and have the same structure. Finally, the first-order condition with respect to the bus price can be written, using the same method, as

$$\begin{aligned}
& (p_g - c_g - \theta_g) \left(\pi_g \frac{\partial x_c^g}{\partial p_b} + x_c^g \frac{\partial \pi_g}{\partial p_b} \right) + (p_d - c_d - \theta_d) \left(x_c^d \frac{\partial \pi_d}{\partial p_b} + \pi_d \frac{\partial x_c^d}{\partial p_b} \right) \\
& + (p_b - c_b - \theta_b) \left[\pi_g \frac{\partial x_b^g}{\partial p_b} + x_b^g \frac{\partial \pi_g}{\partial p_b} + \pi_d \frac{\partial x_b^d}{\partial p_b} + x_b^d \frac{\partial \pi_d}{\partial p_b} + \pi_o \frac{\partial x_b^o}{\partial p_b} - x_b^o \left(\frac{\partial \pi_g}{\partial p_b} + \frac{\partial \pi_d}{\partial p_b} \right) \right] \\
& + F_g \frac{\partial \pi_g}{\partial p_b} + F_d \frac{\partial \pi_d}{\partial p_b} = \left(\frac{(m_g - \lambda) \pi_g x_b^g + (m_d - \lambda) \pi_d x_b^d + (m_o - \lambda) \pi_o x_b^o}{\lambda} \right)
\end{aligned} \tag{A.3}$$

Subtracting (A.2) from (A.1) and noting, by differentiation of the probabilities, that

$$\begin{aligned}
\frac{\partial \pi_g}{\partial p_g} &= x_c^g \frac{\partial \pi_g}{\partial F_g} \\
\frac{\partial \pi_d}{\partial p_g} &= x_c^g \frac{\partial \pi_d}{\partial F_g}
\end{aligned}$$

we immediately find

$$(p_g - c_g - \theta_g) \left(\pi_g \frac{\partial x_c^g}{\partial p_g} - x_c^g \pi_g \frac{\partial x_c^g}{\partial F_g} \right) - (p_b - c_b - \theta_b) \left(\pi_g \frac{\partial x_b^g}{\partial p_g} - x_c^g \pi_g \frac{\partial x_b^g}{\partial F_g} \right) = 0$$

Slightly reformulating yields

$$(p_g - c_g - \theta_g) = A (p_b - c_b - \theta_b) \tag{A.4}$$

where

$$A = - \frac{\frac{\partial \hat{x}_b^g}{\partial p_g}}{\frac{\partial \hat{x}_c^g}{\partial p_g}}$$

and the hat refers to compensated demand effects.

Analogous reasoning on the basis of the first-order conditions for p_d and F_d yields, after very similar derivations

$$(p_d - c_d - \theta_d) = B (p_b - c_b - \theta_b) \tag{A.5}$$

where $B = -\frac{\frac{\partial \hat{x}_b^d}{\partial p_d}}{\frac{\partial \hat{x}_c^d}{\partial p_d}}$.

We can now use (A.4)-(A.5) in the three first-order conditions with respect to the variable taxes to eliminate p_g, p_d . Substituting, expressing all demand effects in terms of compensated demands and using

$$\begin{aligned}\frac{\partial \hat{x}_b^g}{\partial p_g} + A \frac{\partial \hat{x}_c^g}{\partial p_g} &= 0 \\ \frac{\partial \hat{x}_b^d}{\partial p_d} + B \frac{\partial \hat{x}_c^d}{\partial p_d} &= 0\end{aligned}$$

yields the following system:

$$D_g(p_b - c_b - \theta_b) + F_g \frac{\partial \hat{\pi}_g}{\partial p_g} + F_d \frac{\partial \hat{\pi}_d}{\partial p_g} = (\alpha_g - 1)\pi_g x_c^g \quad (\text{A.6})$$

$$D_d(p_b - c_b - \theta_b) + F_g \frac{\partial \hat{\pi}_g}{\partial p_d} + F_d \frac{\partial \hat{\pi}_d}{\partial p_d} = (\alpha_d - 1)\pi_d x_c^d \quad (\text{A.7})$$

$$D_b(p_b - c_b - \theta_b) + F_g \frac{\partial \hat{\pi}_g}{\partial p_b} + F_d \frac{\partial \hat{\pi}_d}{\partial p_b} = \bar{\alpha} \quad (\text{A.8})$$

where the notation $\hat{\pi}$ refers to compensated choice probabilities (see Rosen and Small (1981)), and the terms D_i are given by:

$$\begin{aligned}D_g &= (x_b^g - x_b^o + Ax_c^g) \frac{\partial \hat{\pi}_g}{\partial p_g} + (x_b^d - x_b^o + Bx_c^d) \frac{\partial \hat{\pi}_d}{\partial p_g} \\ D_d &= (x_b^g - x_b^o + Ax_c^g) \frac{\partial \hat{\pi}_g}{\partial p_d} + (x_b^d - x_b^o + Bx_c^d) \frac{\partial \hat{\pi}_d}{\partial p_d} \\ D_b &= (x_b^g - x_b^o + Ax_c^g) \frac{\partial \hat{\pi}_g}{\partial p_b} + (x_b^d - x_b^o + Bx_c^d) \frac{\partial \hat{\pi}_d}{\partial p_b}\end{aligned}$$

Finally, the α 's in system (A.6)-(A.7)-(A.8) capture all income effects, both those related to the conditional demands and to the choice probabilities. However, to facilitate the derivation and interpretation of optimal tax rules, we assume in the main body of the paper that the marginal private utility of income is independent of choice of car type (i.e., $m^g = m^d = m^o = m$) and that income effects of conditional demands are zero. In that case one easily shows that

$$(\alpha^g - 1) = (\alpha^d - 1) = \left(\frac{m - \lambda}{\lambda} \right)$$

and
$$\bar{\alpha} = \left(\frac{m - \lambda}{\lambda} \right) (\pi^g x_b^g + \pi^d x_b^d + \pi^o x_b^o)$$

We solve the three-equation system (A.6)-(A.7)-(A.8) by Cramer's rule. A series of straightforward but long manipulations to develop the determinant of the system leads to the solution for the fixed taxes and public transport prices as given in the main body of the paper:

$$p_b - c_b - \theta_b = - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^g}{\partial p_g} \frac{\partial \hat{x}_c^d}{\partial p_d}}{Z} \quad (\text{A.9})$$

$$F_g = - \left(\frac{m - \lambda}{\lambda} \right) \frac{1}{\pi_o m} - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^d}{\partial p_d} \left[\frac{\partial \hat{x}_b^g}{\partial p_g} x_c^g - \frac{\partial \hat{x}_c^g}{\partial p_g} (x_b^g - x_b^o) \right]}{Z} \quad (\text{A.10})$$

$$F_d = - \left(\frac{m - \lambda}{\lambda} \right) \frac{1}{\pi_o m} - \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_c^g}{\partial p_g} \left[\frac{\partial \hat{x}_b^d}{\partial p_d} x_c^d - \frac{\partial \hat{x}_c^d}{\partial p_d} (x_b^d - x_b^o) \right]}{Z} \quad (\text{A.11})$$

The term Z is given by:

$$Z = \pi_g S_g \frac{\partial \hat{x}_c^d}{\partial p_d} + \pi_d S_d \frac{\partial \hat{x}_c^g}{\partial p_g} - \pi_o \frac{\partial \hat{x}_c^g}{\partial p_g} \frac{\partial \hat{x}_c^d}{\partial p_d} \frac{\partial \hat{x}_b^o}{\partial p_b}$$

where
$$S_i = \frac{\partial \hat{x}_b^i}{\partial p_i} \frac{\partial \hat{x}_c^i}{\partial p_b} - \frac{\partial \hat{x}_b^i}{\partial p_b} \frac{\partial \hat{x}_c^i}{\partial p_i} \quad i = g, d$$

are Slutsky terms associated with the conditional utility maximisation problems for gasoline and diesel owners, respectively. The negativity of the Slutsky terms implies that $Z > 0$.

Finally, using (A.9) into (A.4) and (A.5) we obtain the optimal variable car taxes:

$$p_g - c_g - \theta_g = \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_b^g}{\partial p_g} \frac{\partial \hat{x}_c^d}{\partial p_d}}{Z}$$

$$p_d - c_d - \theta_d = \frac{\left[\left(\frac{m - \lambda}{\lambda} \right) x_b^o \right] \frac{\partial \hat{x}_b^d}{\partial p_d} \frac{\partial \hat{x}_c^g}{\partial p_g}}{Z}$$



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