FACULTY OF ECONOMICS AND
APPLIED ECONOMIC SCIENCES
CENTER FOR ECONOMIC STUDIES
ENERGY, TRANSPORT & ENVIRONMENT

KATHOLIEKE
UNIVERSITEIT
LEUVEN

WORKING PAPER SERIES
n°2001-02

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January 2001

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Pricing transport networks with fixed residential location

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Keywords: Congestion, road transport, pricing, networks
JEL Codes: H23, R10, R41, R48

Abstract

We consider a congestible static traffic network which is used by different households and analyse the conditions for optimal congestion taxes on network links, when not all links in the network can be taxed (partial network pricing). This is done under two assumptions about the toll revenues. First, lump sum transfers are assumed to be available. It is shown that social welfare maximisation leads to unequal treatment of equal households, because of differences in transport costs, and that constraints on network pricing imply complex deviations from marginal social cost pricing, because of network interactions.

The second assumption is that the congestion tax revenue is redistributed to households according to predetermined shares. In that case, the optimal link taxes consist of a Pigouvian component, a Ramsey-Mirrlees component and a network interaction component. The taxes will deviate from marginal external congestion costs, even in the absence of network pricing constraints. This result is qualitatively different from the partial equilibrium analysis.

Stylised examples of two networks are used to illustrate (a) the impact of unequal treatment of equals and of tax redistribution rules on optimal link taxes and on their effectiveness in terms of social welfare, and (b) the effect of network pricing constraints. The results suggest that (1) the effectiveness of congestion taxes is strongly reduced when not all links in the network can be taxed, (2) assignment inefficiencies are of less importance than excess demand levels when no taxes are present, and (3) that optimal parking charges may outperform partial pricing schemes when the assignment inefficiencies are small.

[♦] The author acknowledges the support of the Federal Office for Scientific, Technical and Cultural affairs, under the Sustainable Mobility Programme, contract MD/01/026. Earlier versions of the paper have been presented at an ETE-workshop, CES, KULeuven and at the Department of Economics, University of California, Irvine. Participants are thanked for their remarks. In particular, thanks to Stef Proost, Ken Small and Erik Verhoef. The usual disclaimer applies.

1. Introduction

Economic theory suggests that congestion pricing is the preferred way to internalise traffic congestion externalites. Most often the congestion pricing literature has abstracted from spatial aspects in discussing and extending this result. Our goal is to investigate the properties of a welfare maximising congestion pricing system in the context of a congestible static traffic network. More specifically, we consider a network that is simultaneously used by multiple households, who employ several transport modes to produce trips to various destinations.[1] The destinations may or may not be substitutes. The residential location of all consumers is taken to be fixed. Government is assumed to be a social welfare maximiser, with or without access to individualised lump sum transfers and –possibly restricted- taxes on network links. The paper covers three topics.

First, it is shown that the non-convexity in household location choice, which leads to the choice of only one location, implies in general that equal households have different utility levels at the social welfare optimum. This is called Mirrlees inequality, after Mirrlees (1972) who first noted the problem. It follows from the fact that transport costs for the same destination differ between households. We briefly discuss some ways of dealing with this issue. In the Herbert-Stevens model, the social surplus is maximised subject to target utility levels for all households (Fujita, 1990). Since to any Herbert-Stevens model corresponds a social welfare function with particular welfare weights and appropriate lump sum transfers for all households, we will rely on the social welfare maximisation approach for the description of the optimal pricing conditions.

Next the optimal network pricing conditions are derived, allowing for constraints on the set of links which can be taxed, i.e. allowing for partial network pricing. The constraints may be interpreted as limiting congestion pricing to some transport modes, or to some links. In order to focus on the effect of partial pricing we first allow for optimal lump sum transfers. Next we elimitate the lump sum transfers, using ex ante fixed shares instead. The interaction between optimal network prices and Mirrlees inequality is analysed, as well as the role of revenue redistribution.

Finally, simple networks are used to illustrate the impact of Mirrlees inequality and of pricing constraints on the effectiveness of transport pricing schemes in terms of social welfare. The use of a network structure allows to compare various pricing instruments: link congestion tolls, pricing of transport modes, parking charges, transit pricing, uniform pricing, etc. We mainly limit ourselves to partial pricing schemes and to parking charges. It is illustrated that the effectiveness of imperfect schemes may be drastically smaller than that of first best pricing, and that parking charges outperform partial pricing schemes under some conditons. Furthermore, assumptions on tax revenue redistribution strongly affect the optimal tax structure.

The main contributions of the present analysis are (a) to emphasise the impact of transport cost differences, caused by different locations, on the welfare properties of an optimal pricing scheme, (b) to provide a second-best network pricing rule within a simple general equilibrium context, and (c) to clarify that optimal network prices strongly depend on the particular welfare objective, especially

[1] The model is general enough to allow for multiple time periods (e.g. peak, off-peak) and different trip purposes (e.g. leisure-related trips and commuting trips). These topics are not developed in this paper however.

when optimal lump sum transfers are not available. Furthermore, the analysis allows for substitution between destinations and for multimodality, while extension to a multiperiod framework is straightforward.

The most important analytical simplification is the assumption that location is fixed. Apart from the fact that this requires us to allow for individualised rather than uniform lump sum transfers, the assumption is not very restrictive. In particular, endogenising household location choice, e.g. by introducing a land market, would add to the analytical complexity but would not sidestep the issue of Mirrlees inequality. This problem is caused by the non-convexity of preferences, hence it also appears in endogenous location models. The interaction between transport prices and residential location choice is abstracted from in this paper, but we do allow for changes in choice of destination in response to changing transport prices. Therefore our analysis can be taken to represent a short to medium run assessment of the spatial impacts of transport network pricing.

Section 2 ties the present analysis to various strands of the congestion pricing literature. The theoretical analysis, with the discussion of the social welfare objective and the optimal pricing conditions, is in section 3. Section 4 discusses the effectiveness of partial pricing schemes by means of an example. Section 5 concludes.

2. Literature on partial transport network pricing

We briefly discuss three relevant strands of the literature: (a) economic analyses of pricing of two parallel links, (b) analysis of partial network tolling in transportation science, and (c) economic analysis of pricing general static traffic networks.

The economic literature on congestion pricing has most often implicitly assumed that all links in the network can be taxed. Otherwise, the analysis of network effects has been limited mainly to the case of one origin-destination pair connected by two links. This strand of the literature can be traced back to Knight’s (1924) comment on Pigou (1920), which states that inefficient pricing disappears under private road ownership, given sufficient competition. In the absence of competition for road ownership, a monopoly road owner will internalise marginal external congestion costs and charge a mark-up depending on the price elasticity of demand (Small, 1992). A related question concerns the situation where a privately and a publicly owned road between the same origin and destination co-exist. Various authors (Marchand, 1968; McDonald, 1995; Braid, 1996; Verhoef et al., 1996; Liu and McDonald, 1999; Arnott et al., 1996) have studied this problem, usually assuming that the private road is tolled and the public road is not.

The analytical results depend to some extent on the representation of congestion. The traditional flow congestion model represents the time cost of road use as an increasing function of flow (per unit of time). The bottleneck model describes the formation of a queue at a bottleneck, in case demand exceeds capacity of this bottleneck. Departure time is endogenous in this model.

Concerning one-link pricing in a two-link model, the fundamental results for the flow congestion model are that:

- The optimal tax is the result of a trade-off between the objectives of aggregate demand reduction and optimal assignment of traffic flows. The first objective pushes the tax up, the second may push it up or down, depending on the cost characteristics of the two routes.

- The relative efficiency of second-best taxes decreases as the price elasticity of demand rises.
- The relative efficiency of second-best taxes increases as the tolled route is shorter and less congestible.

The introduction of consumer heterogeneity increases the relative welfare gain obtained from partial pricing schemes: pricing only one road leads to separating equilibria, which mitigates the welfare loss of the partial pricing scheme (Verhoef and Small, 1999; Small and Yan, 2001). In line with earlier studies on equity effects of road pricing, the model predicts welfare gains or losses for users with different values of time (different user classes).

The basic insight from the bottleneck congestion model is that the optimal tax consists of a positive and time dependent component to prevent queueing on the tolled route and of a negative uniform component which is meant to alleviate congestion on the untolled route. De Palma and Lindsey (2000) analyse competition between two roads for a wider set of ownership arrangements and allow tolling on both roads.

The main results from the second best pricing literature in two link networks are that (a) second-best schemes can be effective for reallocating traffic flows, (b) second-best taxes are much smaller than first-best taxes, and (c) second-best taxes produce much smaller welfare gains than first-best taxes. These results are confirmed for a wide range of models and parameter values.

Congestion pricing in a multimodal network affects transport demand levels, mode choice and path choice. Path choice, or network assignment, is an important research area in transportation science. In the most basic static traffic network model (e.g. Sheffi, 1985), network users behave as travel cost-mimimisers, in a non-coordinated fashion. Wardrop (1952) shows that this leads to equal average travel costs for all used paths between an origin and a destination. This is not a welfare maximising solution, in which marginal travel costs are equalised over all used paths belonging to the same origin-destination pair. Only recently, attention has gone to the design of optimal partial pricing schemes. Contributions in this area focus on mathematical properties and on algorithm design. Construction of general algorithms is not straightforward given the combinatorial aspects of the problem (Larsson and Patriksson, 1998, Labbé et al., 1998; Ferris et al., 2000).

An economic analysis of optimal partial pricing systems in general static networks is in Verhoef (1998), who employs a partial equilibrium approach. Demand for an origin-destination pair depends on the price of that origin-destination pair only, and social welfare is the sum of Marshallian consumer surplusses in all origin-destination markets. The optimal second-best link tax is seen to depend on the pricing conditions on other links, as well as on cost and demand interactions. It may be above or below external congestion costs on the link. The optimal second-best tax configuration is not necessarily unique. A first-best solution is to set all link taxes equal to marginal external costs on the link. Our analysis generalises the second-best pricing rule, drawing attention to the importance of assumptions on the availability of individualised lump sum transfers and on the redistribution of congestion tax revenues. Instead of the primal formulation of the optimal tax problem (which is implicit in the partial equilibrium analysis), we will be using the more convenient dual approach. It will be shown that the partial equilibrium results hold as long as individualised lump sum transfers are available, but not under other assumptions on tax instruments and tax revenue redistribution. It will, e.g., not be the case that marginal social cost pricing is optimal when all links in the network can be taxed.

3. Theory

This section starts with the representation of the network and its usage by consumers. Subsequently we discuss the government problem under first best and second best network pricing conditions.

3.1 Consumer equilibrium in a static transport network

Denote a static transport network by a graph *G(N,A)* , where *N* is a set of nodes and *A* a set of links. The graph is strongly connected, so that each node can be reached from every other node through at least one sequence of links. Such a sequence is called a path. Links are congestible when time costs (c_a) are increasing in traffic flow on the link (f_a, in passenger car units per unit of time): $\left(\frac{d c_a}{d f_a} \equiv c'_a\right) \geq 0, \forall a \in A$.[2] The network technology is simplified by assuming $\frac{d c_a}{d f_b} = 0, \forall a \neq b \in A$.

Consider N_i identical consumers at each trip origin $i=1,\ldots,I$ in the network ($i \in N, \forall i$). The trip origin coincides with residential location, and it is fixed. Consumers' utility functions (3.1) are defined over a composite numéraire commodity x_i and over transport commodities $q^r_{i,j}$.[3] Each $j=1,\ldots,J$ represents a trip destination ($j \in N, \forall j$). Trip origins and destinations are connected by paths *r*. The set of paths is denoted $P_{i,j}$. The utility functions are assumed to possess all regularity conditions to allow for an optimal taxation analysis.

$$U_i = U_i\left(x_i, \mathbf{q^r_{i,j}}\right), \forall i = 1,\ldots, I \text{ where } j = 1,\ldots, J \text{ and } r \in P_{i,j} \tag{3.1}$$

A path represents a route for a given transport mode, or it refers to different transport modes. Link flow is then defined as the sum of demands for all paths that use the link: $f_a = \sum_i \sum_j \sum_{r \in P_{i,j}} d^a_{i,j,r} N_i q^r_{i,j}, \forall a$.[4] The indicator variable $d^a_{i,j,r}$ equals 1 when *link a* belongs to path r, and zero otherwise.

Substitution between destinations is allowed for. In reality, the degree of substitutability depends on the trip motive and on the time horizon. Shopping destinations may be thought of as substitutable in the short run. Commuting destinations, or employment locations, probably only exhibit a significant degree of substitutability in the long run.

[2] Allowing for zero derivatives is useful for the introduction of virtual links, which may represent flow independent costs (e.g. parking costs, waiting times, or some types of taxes).

[3] Since transport is actually a derived demand, specifying transport as an argument of the utility function is a reduced form.

[4] In principle a conversion from trip demand to flow in terms of passenger car units is required, when transport modes with different occupancy rates are considered. We abstract from this in the theoretical analysis, for reasons of clarity.

Each household faces a budget constraint (3.2). The exogenous income Y_i, the lump sum transfer T_i, transport time costs c_a and taxes t_a are stated in generalised terms. This implies that the value of marginal time savings or losses is taken to be constant. The consumer price of a commodity $q^r_{i,j}$ is the sum of time costs and taxes incurred on all network links which are used to reach destination j, starting from origin i and using path r.

$$Y_i + T_i = x_i + \sum_j \sum_r \left(\sum_a d^a_{i,j,r} (c_a + t_a) q^r_{i,j} \right) \forall i \tag{3.2}$$

Using l_i as multiplier for the budget constraint, the first order conditions for maximising (3.1) subject to (3.2) and non-negativity constraints, are given by equations (3.3) and (3.4). Households neglect the congestion externality. When paths are perfect substitutes, condition (3.4) implies that the prices on all paths $r \in P_{i,j}$ which carry positive flow are equal and not larger than prices on all paths $s \in P_{i,j}$ that do not carry any flow, see (3.5). This corresponds to the Wardropian network equilibrium conditions (Wardrop, 1952), which thus are a special case of the present specification. In order to simplify notation, the subsequent analysis abstracts from the complementarity condition by considering paths with positive flow only.

$$\frac{dU_i}{dx_i} = l_i, \forall i \tag{3.3}$$

$$\frac{dU_i}{dq^r_{i,j}} = l_i \left(\sum_a d^a_{i,j,r} (c_a + t_a) \right), \forall i, \forall j, r : q^r_{i,j} \gg 0 \tag{3.4}$$

$$\left(\sum_a d^a_{i,j,r} (c_a + t_a) \right) = \left(\sum_b d^b_{i,j,s} (c_b + t_b) \right) \text{ if } q^r_{i,j} \gg 0, q^s_{i,j} \gg 0 \tag{3.5}$$

The indirect utility function is given by $V_i(c_a+t_a, a=1,\ldots,A, Y_i+T_i)$, *for all* i. As congestion is not an argument of the utility function as such, external congestion costs, which on the link level equal $c'_a f_a$, are valued at the marginal utility of income.

3.2 Optimal congestion pricing in a static transport network

In section 3.2.1 the concept of Mirrlees inequality is introduced, using a simple network example. Next, section 3.2.2 presents the optimal tax structure in case government maximises social welfare by using individualised lump sum transfers T_i and a restricted set of link taxes t_a. Restrictions on link taxes are indicated by k_a, which equals one when a link tax is possible and zero otherwise. The nature of the restriction implies that when a link tax is possible, it can take any value. Allowing for a lump sum transfer simplifies the analysis, as the congestion externality is the only remaining inefficiency. The justification is that it allows us to focus on two main topics. First, the lump sum transfer clarifies how unequal treatment of equal households affects the optimal tax structure, as the transfer is used to equalise social marginal utilities of income. Second, it allows to emphasise the impact of restrictions on link taxes (partial network pricing) on optimal congestion taxes. The main simplification in section 3.2.2 is to allow for a lump sum transfer, not the fact that it is individualised to each household. The latter is required because of the absence of an equilibrating mechanism, such as a land market, in the model. The individualised transfer makes it possible for households with equal preferences to enjoy equal utilities at different residential locations.

In section 3.2.3 it is assumed that lump sum transfers can not be optimised, but that each household receives a given share of the congestion tax revenues. Optimal link taxes then are seen to interact with Mirrlees inequality. This is clarified by a decompostion of the link tax expression into three terms: a Pigouvian term, relating to external congestion costs on the link, a Ramsey-Mirrlees term, relating to transport cost differences, and a network interaction term, relating to restrictions on link taxes. The optimal link taxes will be seen to deviate from marginal external congestion costs on the link, also when all links in the network can be taxed.

3.2.1 Welfare maximisation with Mirrlees inequality

Mirrlees (1972) showed that in a spatial model of land use, maximisation of a social welfare function implies unequal treatment of equal households at the optimum. In the market equilibrium for a monocentric city model, households with identical preferences and incomes realise equal utilities at all locations. As households face different transport costs to the city centre, their marginal utilities of income differ. More specifically, when land rents compensate for the transport cost differences, the marginal utility of income is higher for households residing further out from the centre. This is exploited by the social welfare maximisation, in the sense that households with higher marginal utilities of income are advantaged. Hence the interaction with the land market implies that in a monocentric city households residing further out from the centre have higher utility in the social optimum (see e.g. Straszheim, 1986). Arnott and Riley (1977) show that the issue arises whenever production asymmetries exist, i.e. when a commodity can be produced more cheaply for one household than for another. Unequal treatment of equal households arises whenever a non-Rawlsian, symmetrical and quasi-concave social welfare function is used.

The source of the problem (in the monocentric city model as well as in the present model) is that restricting household location choice to the choice of one location, implies the assumption that preferences over locations are non-convex (Fujita, 1990). When locations differ between households, transport costs for the same destination differ. In the context of a static transport network, different locations imply the use of different paths to reach the same destination. The difference in transport costs causes the production costs for possibly identical consumers to differ, so that the utility possibility frontier is asymmetrical. This is illustrated in figures 3.1 and 3.2.

Figure 3.1 displays a network consisting of two *links a and b* with link costs $c_a>0$ and $c_b>0$. Household 1 uses *links a and b* (alternatively, *path ab*) to reach destination D. Household 2 uses *link b*. Both households have identical preferences (as described by equation (3.1)), but face different transport costs. We assume that in the no intervention equilibrium household utilities are equal. Since our model contains no compensating land market, the transport cost differences imply that the income for household 2 is lower than for household 1. The marginal utility of income is higher for household 2 than for household 1.[5] The utility possibility frontier for this economy (figure 3.2) is given by curve

[5] Hence, in contrast to the monocentric city model, the marginal utility of income is higher for households living closer to the trip destination. This implies that in our model, the direction of the unequal

CB instead of CA. The Pareto-efficient point where both households are treated equally is D. This point can not be reached unless a Rawlsian social welfare function is used. In fact, the optimal point lies between the extremes D and E (e.g. E'), where E is optimal under a Benthamite social welfare function (which exhibits no inequality aversion, and therefore maximally exploits the transport cost differences).

Figure 3.1 **A two serial links network with two household locations and one destination**

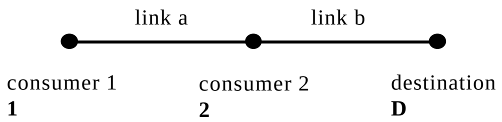
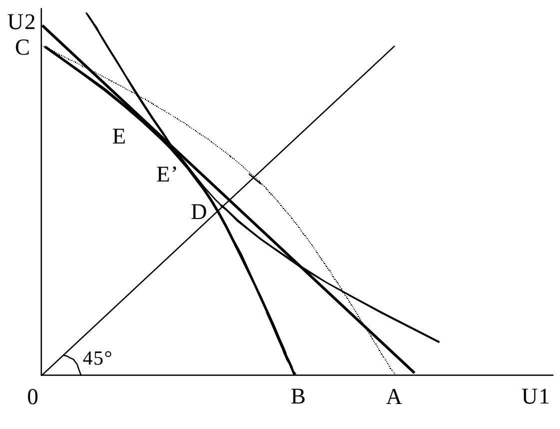


Figure 3.2 **Utility possibility frontier and social welfare optima with differing transport costs**



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treatment of households is reversed in comparison to the monocentric city model. Appendix 1 explains the differences between both approaches graphically.

One way of dealing with Mirrlees inequality is to accept it. The optimal lump sum transfer and the associated market equilibrium can be computed. This equilibrium then is a benchmark to which the benefits of network congestion taxes can be measured. The government budget constraint for this case is given by (3.6). Alternatively, as unequal treatment of equal households may not be desirable from a normative point of view, it can be restricted. In general this can be done by restricting the transfers, or by imposing target utility levels.

$$\sum_i T_i = \sum_a k_a t_a f_a \tag{3.6}$$

The transfers can be restricted by requiring that they are financed only by congestion tax revenues. The congestion tax revenues can be redistributed to households in various ways. Equation (3.7) corresponds to a system where each household is compensated by exactly the amount of taxes it pays, while equation (3.8) refers to redistribution of tax revenues according to given shares s_i. As will be illustrated in section 3.2.3, restricting the transfers does not neutralise the social welfare impact of Mirrlees inequality. The optimal tax structure and the tax levels are affected by the tendency to increase the utility of households with low transport costs.

$$T_i = \sum_j \sum_r \left(\sum_a d^a_{i,j,r} k_a t_a q^r_{i,j} \right), \forall i \tag{3.7}$$

$$T_i = \frac{s_i}{N_i} \sum_a k_a t_a f_a, \forall i, \text{ where } \sum_i N_i s_i = 1 \tag{3.8}$$

Imposing target utility levels can be done by computing Pareto-improvements, i.e. fixing utility levels of all but one households to the reference utility level. Alternatively a target utility level may be specified for all households. This is called the Herbert-Stevens approach (Fujita, 1990). The social welfare criterion then is to minimise the costs of attaining these utility levels. As incomes are taken to be fixed, this can be reformulated as maximising a social surplus, which is equal to total available income less the costs of reaching the target utilities. As the target utilities must be reached in a way consistent with household preferences, the minimal costs can be computed through the expenditure function. This function assumes that income is sufficient to attain the target utility, so that lump sum transfers are implicitly allowed. The surplus (deficit) which remains after subtraction of the costs for reaching the target utilities, is interpreted as a benefit (cost) to the rest of the economy.

There is no theoretical reason to prefer Herbert-Stevens over social welfare maximisation, as it can be seen that to each Herbert-Stevens model (i.e. to each set of target utilities) corresponds a social welfare maximisation programme with particular welfare weights for each household and with lump sum transfers available. This is the case as long as the optimal allocation as determined by a social welfare function, is invariant with respect to the total income which is available in the economy. The main characteristic of the Herbert-Stevens approach -full control over target utilities- may nevertheless be useful in computational applications, as no ex ante information on social welfare weights is required. The degree of unequal treatment of equals can be controlled by the modeller. The downside of the approach lies in the interpretation of the surplus as a transfer to the rest of the economy. For the further analysis the standard social welfare approach will be used, as it describes optimal pricing conditions for particular welfare weights or for particular utility targets.

3.2.2 Optimal network pricing with individualised lump sum transfers

Maximising programme (3.9) using transfers T_i and available link taxes t_a produces first order conditions (3.10) and (3.11). The lump sum transfer is used to equalise social marginal utilities of income, and the social welfare evaluation of the effect on indirect utilities of a link tax change is equalised to the social value of the tax revenue change.

$$\Im = W\left(N_i V_i, i = 1,\dots, I\right) + m\left(\sum_a \left(\sum_i \sum_j \sum_r d^a_{i,j,r} k_a t_a N_i q^r_{i,j}\right) - \sum_i N_i T_i\right) \tag{3.9}$$

$$\frac{dW}{dV_i} = \frac{m}{l_i}, \forall i \tag{3.10}$$

$$\sum_i N_i \frac{dW}{dV_i}\frac{dV_i}{dt_a} + m\left(\sum_i \sum_j \sum_r d^a_{i,j,r} N_i q^r_{i,j} + \sum_b k_b t_b \frac{d\,f_b}{d\,t_a}\right) = 0, \forall a : k_a = 1 \tag{3.11}$$

Equation (3.12) gives the indirect utility effect of a marginal change in the link tax. Substituting (3.10) and (3.12) in all conditions (3.11) where $k_a=1$, using the definition of link flow, and solving the system of $\sum_a k_a$ equations for t_a, produces (3.13).

$$\frac{dV_i}{dt_a} = -l_i\left(\sum_r \sum_j d^a_{i,j,r} q^r_{i,j} + \sum_r \sum_j \left(\sum_b d^b_{i,j,r} c'_b\, q^r_{i,j} \frac{d\,f_b}{d\,t_a}\right)\right), \forall i, a : k_a = 1 \tag{3.12}$$

$$t_a = c'_a\, f_a + \sum_{z:k_z=1} \left(\frac{\sum_{b\neq a}\left(c'_b\, f_b - k_b t_b\right)\frac{d\,f_b}{d\,t_z}}{\frac{d\,f_a}{d\,t_z}}\right), \forall a : k_a = 1; b, z \in A \tag{3.13}$$

From (3.13) it is easily observed that when $k_a=1$ for all a, setting all link taxes equal to marginal external costs on the link ($t_a = c'_a f_a$) satisfies the optimality conditions. This is not necessarily the only possible tax configuration, as the network topology may allow equivalent tax systems. The condition is that taxes on each path for each consumer and each destination equal marginal external costs. In some networks this can be achieved without marginal social cost pricing on each link. An example is the network depicted in figure 3.1. If this network is used by one consumer located at point 1, taxing *link a* or *link b* for the full marginal external congestion costs of *path ab* is efficient. Adding a second consumer at point 2 leaves marginal social cost pricing on each link as the only possibility. In any non-trivial network with a large number of links, paths and consumers, the existence of equivalent systems becomes less likely.[6] We therefore conclude that in general the combination of marginal social cost pricing and optimal transfers is the only solution to the first best network pricing problem.

Now consider the case where $k_a=1$ for one link in the network only, i.e. only one link can be taxed. (3.13) then reduces to (3.14). In the latter, the tax t_a differs from marginal external congestion costs by the marginal effect of a reduction in f_a, caused by a rise in t_a, on congestion on other links. This marginal effect on other links is corrected for the marginal effect on the link under consideration. The denominator is negative. The numerator takes either sign, leaving the sign of the correction factor undetermined in general. Observe that the other *links b* belong to 2 classes. Class 1 contains links that belong to paths which also contain *link a*: $C1=\left\{b\in A: d^{b}_{i,j,r}=d^{a}_{i,j,r}=1,\forall i,j,r\right\}$. Class 2 contains links that belong to paths that do not contain *link a*: $C2=\left\{b\in A: d^{b}_{i,j,r}=1 \text{ and } d^{a}_{i,j,r}=0,\forall i,j,r\right\}$. The intersection of C1 and C2 is non-empty, as any link can both be part of a path of which a link is taxed and of other paths which are not being taxed. For links in C1, a marginal increase in t_a decreases flow. For C2, flow increases as far as the links are used for substitute paths or substitute destinations. The sign of the second term in (3.14) depends on the relative importance of both classes of links in terms of flow, on the slope of the cost function of those links, and on the size of the flow reactions. When C2 is relatively large, t_a tends to drop below $c'_a f_a$. This occurs when alternative paths are available which are perfect substitutes, in which case a high t_a distorts the assignment of traffic on the network too much. A second possibility is that a consumer has the choice between two substitute destinations. Excessive taxation of the path to one shopping destination causes excessive congestion on paths leading to the other one. Only when t_a belongs to paths which can not be easily substituted, will the tax rise above marginal external congestion costs.

$$t_a = c'_a\, f_a + \frac{\sum_{b\neq a} c'_b\, f_b \dfrac{d\, f_b}{d t_a}}{\dfrac{d\, f_a}{d t_a}} \tag{3.14}$$

Returning to (3.13), it can be seen that the general second best tax expression has a similar interpretation to (3.14). One difference is that account should be taken of the deviation between taxes and marginal external costs on all other links. The second difference is that the marginal flow effects of all possible link taxes on all links matter for the determination of the optimal t_a. Section 4.3 illustrates the empirical relevance of the network interactions in terms of welfare effects and tax levels.

3.2.3 Optimal network pricing with restricted lump sum transfers

When all links in the network can be taxed and when optimal lump sum transfers are available, marginal social cost pricing constitutes a possible solution to the network pricing problem. Distributional issues are addressed through the transfers, whatever the social welfare weights are. This

[6] The only degree of freedom in setting link taxes in a context of variable transport demand is the case discussed in the text. This degree of freedom disappears when the two links are collapsed into one, i.e. when the network graph is constructed with the minimal number of links. In a fixed demand setting, multiple tolling equilibria are the rule rather than the exception (Larsson and Patriksson, 1998).

separation of tax functions holds when not all links can be taxed, as long as lump sum transfers can be optimised.[7] Congestion taxes will be set optimally according to the first order conditions for the network taxes, implying deviations from marginal social cost pricing. Optimal transfers are used to optimally redistribute income, given the link taxes. The analysis changes when lump sum transfers are restricted, as this implies that link taxes are used for redistributional purposes, irrespective of link tax constraints.

In general, when optimal lump sum transfers are not available, it is the case that $t_a = t_a\left(c'_b\ f_b, k_b, \forall b \in A; V_i, \dfrac{dW}{dV_i} N_i, i = 1,...,I \right)$, that is: link taxes depend on congestion and pricing constraints on the network, on preferences, and on the welfare weights of the households who use the network. Therefore, the unequal treatment of equal households is reflected in the optimal link taxes. Some insight into this interaction can be gained from considering a simple network (cfr figure 3.1). The network consists of 2 serial links, which connect the residence of two representative identical households to a common destination *D*. The demand for this destination is denoted D_1 and D_2. Both links are congestible. *Link b* is shared by both households. The flow on *link a* is D_1, the flow on *link b* equals D_1+D_2. In the no-tax equilibrium, incomes are such that household utilities are equal. This implies a higher income for household 1 than for household 2, and a higher marginal utility of income for household 2 than for household 1. Assume a Benthamite social welfare function (i.e. no correction for Mirrlees inequality through inequality aversion), and assume that congestion tax revenues are redistributed in a lump sum way according to a predetermined share *s* for household 1 and *(1-s)* for household 2, see (3.8). Government then solves programme (3.15), which is equivalent to maximising the sum of indirect utilities after substitution of tax revenue into the indirect utility functions. Therefore, $l_i = \mu_i,\ \forall i$. Since transport costs are higher for household 1, we get that $\mu_1 < \mu_2$. Denote this by $\mu_1 = a\mu_2$, with $0 < a < 1$.

$$\begin{aligned}\Im = V_1 + V_2 + m_1 \left(s\left(k_a t_a D_1 + k_b t_b \left(D_1 + D_2\right)\right) - T_1 \right) \\ + m_2 \left((1-s)\left(k_a t_a D_1 + k_b t_b \left(D_1 + D_2\right)\right) - T_2 \right)\end{aligned} \tag{3.15}$$

From the first order condition for t_a we get (3.16), or equivalently (3.17). It describes the condition for the optimal tax for a given level of t_b. Similar expressions can be found for t_b.

$$t_a = \left(\frac{a}{as - s + 1} \right) c'_a D_1 - \left(1 - \frac{a}{as - s + 1} \right) \frac{D_1}{\dfrac{dD_1}{dt_a}} - \left(k_b t_b - c'_b \frac{a D_1 + D_2}{as - s + 1} \right) \tag{3.16}$$

[7] In other words, the presence of a non-convexity in location choice does not prevent application of the second theorem of welfare economics. The normative properties of the social welfare optimum –unequal treatment of households with identical preferences- may not be appealing however.

$$t_a = \frac{wc'_a D_1 + \left(k_b t_b - wc'_b \left(D_1 + \frac{D_2}{\alpha} \right) \right)}{1 - \frac{(1-w)}{\left| e_{1a} \right|}} \tag{3.17}$$

$$\text{where } w = \frac{\alpha}{\alpha s - s + 1}$$

The first term on the right hand side of (3.16) states that a fraction of marginal external congestion costs on *link a* is charged. We call this the *Pigouvian component* of the link tax. The second term relates to demand effects, and it gets a weight equal to one minus the weight of the Pigouvian component. It is called the *Ramsey-Mirrlees component* of the link tax, where 'Ramsey' refers to its dependence on the price elasticity of demand, and 'Mirrlees' to the fact that the term appears because of the existence of transport cost differences. The weight of the first (second) term is positive and increasing (decreasing) in α and in s. An increase in α implies an increase of the relative social welfare contribution of household 1, and causes the tax to be closer to the marginal external cost. In general, such an increase could follow from attaching a higher weight to household 1 in the social welfare function, or from a decrease in the transport cost difference between both households. An increase in s means, in the example, that more of the tax revenue goes to household 1, the household with higher transport costs. This is equivalent to saying that congestion tax revenues can be used less easily to exploit Mirrlees inequality. Consequently, the tax is closer to a Pigouvian tax while the Ramsey-Mirrlees component drops. As can be seen from (3.17), the Ramsey-Mirrlees component implies that the tax decreases as the price elasticity of demand for D_1 rises.

The third term on the right of (3.16) is the *network interaction component* of the tax. It shows that t_a is corrected for the deviation of t_b from the social welfare value of congestion on *link b* (D_1 is weighted by α). The network interaction term is increasing in α and in s, implying that using t_a as an indirect way of addressing congestion externalities on *link b* becomes more and more feasible as the social welfare contribution of household 1 increases. This stands to reason, as in the example only household 1 uses both links. Therefore, the larger the social welfare impact of household 1, the more the network tax system is directed towards internalising the externalities affecting household 1. The indirect effects on household 2 receive less attention.

Notice that t_a differs from marginal external costs on *link a* as long as $\alpha<1$, i.e. as long as transport cost differences exist. This is the case irrespective of whether *link b* can be taxed. When $\alpha=1$, the Ramsey-Mirrlees component reduces to zero, and t_a equals marginal external congestion costs on *link a* in case both links can be taxed (which implies a zero network interaction term).

To conclude, equations (3.16) and (3.17) illustrate that, in the absence of optimal lump sum transfers, optimal link taxes consist of a Pigouvian, a Ramsey-Mirrlees and a network interaction component. The importance of the components depends on the shape of the social welfare function, on the redistribution of congestion tax revenues and on network interactions (including pricing conditions in the network). All tax components are different from zero, also when all links in the network can be taxed optimally, because of the interaction between Mirrlees inequality and network taxes. This interaction disappears only when optimal lump sum transfers are possible or when all households share the same location.

4. Examples

4.1 Properties of the network examples

This section presents empirical illustrations of the main issues which were introduced in the theoretical analysis, on the basis of two examples. The examples are stylised and are not meant to generate definitive policy conclusions. Nevertheless, they are derived from realistic network cost and demand data (obtained from a network model for the city of Namur, Belgium), in order to obtain reasonable orders of magnitude for the model parameters. Appendix 2 contains an overview of the background to the examples. First, the network of figure 3.1 is given a numerical content in section 4.2, so that the importance of the impact of Mirrlees inequality can be evaluated under various tax redistribution assumptions. Second, section 4.3 assumes that individualised lump sum transfers compensate each household exactly for the amount of congestion taxes it pays. This neutralises Mirrlees inequality as much as possible, allowing us to focus on the impacts of network pricing restrictions in a three link network.

The size of the examples is the minimal size which captures the relevant interactions described in section 3. For the analysis of the impact of Mirrlees inequality, a network of two serial links used by households at two different locations who have one common destination (see figure 3.1), is sufficient. The analysis of network interactions under partial pricing uses a three link network (figure 4.4). The impact of preference and cost characteristics on the effectiveness of partial pricing schemes is clarified by sensitivity analysis.

Determination of optimal link congestion taxes when not all links in the network can be taxed, is computationally difficult for a general network graph. Recent research in transportation science focusses on the design of algorithms for optimal partial network pricing (e.g. Labbé et al, 1998). Difficulties arise when the set of paths which are actually used for each origin-destination pair is endogenous. Introduction of link tolls may then induce the usage of paths which were not used before the price change, and vice versa. This turns the problem into a mixed integer or a combinatorial programme, which is difficult to solve, even for small networks. When the set of used paths is exogenous, the partial network pricing problem is an instance of inverse optimisation. In inverse optimisation, cost function parameters are found which turn a given solution into the optimal solution. The simplest case of a network in which the set of paths is exogenous, is a network in which all paths are used. This will be our assumption, so that standard nonlinear optimisation algorithms can be used (the models are programmed in GAMS (Brooke et al, 1996) and solved using CONOPT).

In all examples, household preferences are represented by nested CES functions, defined over a composite commodity and over trip destinations: $U_i = U_i\left(x_i, T_i\left(\mathbf{q_{i,j}}\right)\right), \forall i$, where T_i is the sub-utility function for transport commodities. The elasticities of substitution, which determine the curvature of the indifference curves, are chosen so as to approximate a price elasticity of transport demand of –0.3 in the reference equilibrium. This value is in line with the literature (e.g. Small, 1992). The remaining information required for the calibration of the utility functions is taken from the cost and demand data of the Namur network model. A Benthamite social welfare function is used, meaning that social welfare is the sum of household utilities. Finally we note that, while the theoretical analysis allows for negative taxes, they will be bounded below at zero in the applications.

4.2 Example 1: Mirrlees inequality in a two link serial network

The first example illustrates the impact of differences in transport costs on optimal network prices. For the network configuration depicted in figure 3.1, we assume that both links are 2 km long. The linear approximations to the user cost functions, the reference demands for the representative consumers at each origin, the link flows and the user costs are in table 4.1. The reference equilibrium is constructed so that the utility of households at both locations is equal. This implies that per capita income for households at location 2 is 4.2% lower that for those at location 1, in the assumption that the transport expenditures contained in the example represent 10% of total expenditures.[8] The remaining 90% is spent on a composite numéraire commodity. The monetary value of the marginal utility of income in the reference situation is 0.851 Euro for households 1 and 0.888 Euro for households 2.

Table 4.1 Cost and demand characteristics of the two link network (reference equilibrium)

Aggregate demand (trips)

1 – D	2583
2 – D	1227

Costs (Eurocent) and flow (vehicles)

	Intercept	Slope	Flow	Link travel cost
Link a	20	0.01	2583	45.83
Link b	45	0.01	3672	83.097

Full exploitation of Mirrlees inequality implies that income from households at location 1 is transferred to consumers at location 2 up to the point where the social marginal utility of income is equalised across households. In this particular example this implies transferring all income to households at location 2. This is the ultimate consequence of abstracting from land markets and from crowding externalities at each location. Possible alternatives are to compute Herbert-Stevens optima, or to restrict the amount of lump sum transfers to the amount of congestion tax revenue raised. With respect to Herbert-Stevens optima, it can be shown that any combination of target utility levels can be reached at lower costs when link taxes are available, and that any given utility level can be reached at lower cost for households at location 2 than for those at location 1. Taxing *link a* consequently generates a larger surplus than taxing *link b*, for identical target utilities.

The social welfare gains from optimal transport prices in the example are limited, because congestion is small. When households 1 receive all the congestion tax revenues, welfare increases by 0.2%, and this gain linearly increases to 0.4% when households 2 receive all the revenues. Further impacts of restricting lump sum transfers according to an exogenous redistribution rule are illustrated in figures 4.1 to 4.3. The horizontal axes show the share of congestion tax revenues which goes to households at

8 This clearly is an overestimate, which is made for computational reasons. Lower expenditure shares would not affect the relative effects of the policies we analyse.

location 2. It is no surprise that utility of 'households 2' is increasing in the tax revenue share when both links are taxed (figure 4.1). More remarkable is that the utility of 'households 1' drops below the reference level, once more than 12% of congestion tax revenues goes to households 2. This indicates that taxes are affected by Mirrlees inequality as well as by marginal congestion costs, as is confirmed in figure 4.3. Taxes are nearly twice as high as marginal external congestion costs on *link a* when households 1 receive all the revenue (in case both links can be taxed, series tA/mecA). The ratio increases as more tax revenues go to households 2, because both the direct tax effects and the income redistribution effects promote the exploitation of Mirrlees inequality. For *link b*, taxes are below marginal external congestion costs except when all tax revenues are given to households 2, in which case they are equal to marginal external congestion costs (in case both links can be taxed, series tB/mecB). When all tax revenues go to households 2, there is no reason to tax below marginal external costs on *link b*, as the efficiency gains from internalisation are not counteracted by transferring income to the high cost households 1. Also, there is no reason for taxing above marginal external costs, as Mirrlees inequality can be exploited fully by the tax on *link a*. Consequently, a tax equal to marginal external costs is obtained on *link b*.

Figure 4.2 shows that the share of households 1 in aggregate social welfare (as given by $N_1V_1/(N_1V_1+N_2V_2)$) decreases strongly as more tax revenues are given to households 2 (in case both links can be taxed, series SW share hh1). The more important message is that the share decreases below the reference level as soon as more than some 12% of congestion tax revenues are redistributed to households 2.

The interaction between partial pricing, tax redistribution assumptions and tax levels is straightforward in this example. Taxing *link a* only, indirectly decreases congestion for households 2, thereby re-enforcing the effects of Mirrlees inequality. The optimal tax is higher than in full network pricing, and it increases above marginal external costs at a quicker rate as the revenue share of households 2 grows (figure 4.3, series tA/mecA(tB=0)).[9] As is shown by figure 4.2, the share of households 1 in social welfare drops compared to full network pricing, and it drops below the reference level as soon as a congestion tax on *link a* is implemented (even if households 1 receive all revenues). When only *link b* can be taxed, the optimal tax is slightly above marginal external costs in case all revenues go to households 1 (figure 4.3). It is also higher than the optimal tax under full network pricing. The desire to use the tax on *link b* to internalise congestion on *link a*, is counteracted by the effect of excessively high taxes on the utility of households 2. When more of the revenue goes to households 2, higher taxes will counteract to a lesser degree the tendency to advantage households 2, so that the tax rises above marginal external costs, at nearly the same rate as under full network pricing. Figure 4.2 illustrates that taxing *link b* only, leads to a higher share of households 1 in social welfare.

Figure 4.2 indicates that partial taxation causes a nearly parallel shift in the welfare share of both households. It is affected by the tax revenue shares to a limited extent only. The effect on link tax restrictions is nearly independent of the effect of tax revenue shares, while both as such have a strong impact on the welfare shares. The independence is not complete however. When all tax revenues go to households 2, taxing *link a* only has nearly the same effect on the welfare distribution as taxing both links.

[9] When all tax revenues go to households 1, the second term in (3.16) equals zero.

A further possibility for restricting lump sum transfers is to impose that each household is compensated by the amount of congestion taxes that it pays. This prevents use of the revenues for exploitation of Mirrlees inequality, but tax levels are still affected by the Ramsey-Mirrlees term. Table 4.2 presents the main results for optimal network pricing under this form of redistribution. Despite the fact that the optimal taxes with full network pricing (row 2) are affected by the Ramsey-Mirrlees term, the share of households in social welfare is virtually unchanged. The deviation between taxes and the marginal external costs is rather small, see columns (4) and (5). Partial pricing also has no significant effect on the distribution of aggregate welfare either. Furthermore, the efficiency gains from partial pricing are nearly as high as those of efficient pricing. When the exploitation of transport cost differences is ruled out, partial taxation is an effective instrument in the two link serial network example. The reason is that congestion in the network is limited, so that the efficiency gains from congestion pricing are small.

Table 4.2 Effects of network pricing with exact compensation[a]

	(1) Utility index households 1	(2) Utility index households 2	(3) SW share households 1	(4) tA/mecA	(5) tB/mecB
tA=0, tB=0	1	1	0.703	0	0
tA*, tB*	1.0024	1.0018	0.704	1.083	0.963
tA*, tB=0	1.00015	1.0022	0.703	2.492	0
tA=0, tB*	1.0027	1.0005	0.704	0	1.406

[a] The * sign indicates that a tax is optimised.

In summary, the example illustrates that the interaction between Mirrlees inequality and network externalities leads to deviations of optimal taxes from marginal external costs. This is the case with full and with partial network pricing, and the deviations depend on the specific tax redistribution assumptions. With full network pricing, links which are predominantly used by households with low transport costs tend to be priced below marginal social cost, and those mostly used by households with high transport costs are priced above social cost. This tendency is re-inforced as the tax redistribution mechanism favours low cost households. It is clear that deviations between taxes and marginal external congestion costs under partial network pricing are not only explained by network interaction, but that account must be taken of the Ramsey-Mirrlees effect as well. In the example, this is shown by the faster increase of the tax on *link a* above marginal external congestion costs when only *link a* can be taxed, as compared to full network pricing. Finally, the impact of the Ramsey-Mirrlees term is neutralised to a large extent (but not completely) when each household is compensated by exactly the amount of congestion taxes it pays. We will use this assumption in the next example, enabling ourselves to focus on the importance of link tax restrictions.

Figure 4.1 Household utility index with full network pricing

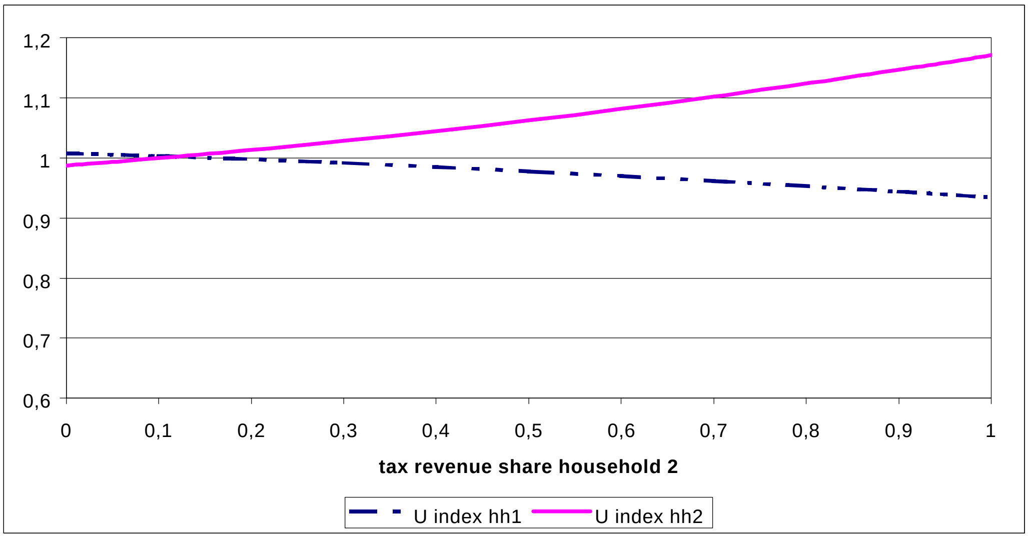


Figure 4.2 Distribution of social welfare with full and partial network pricing[10]

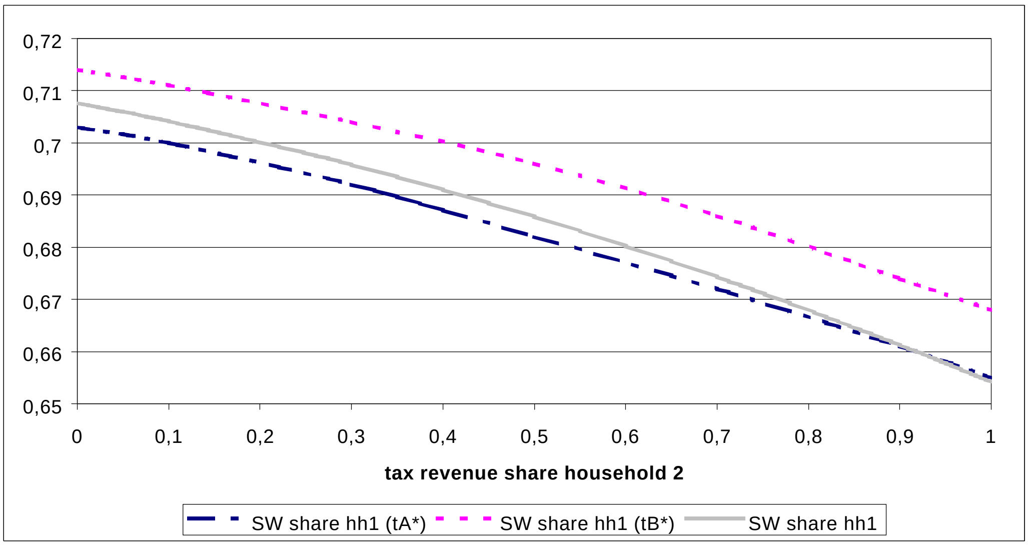
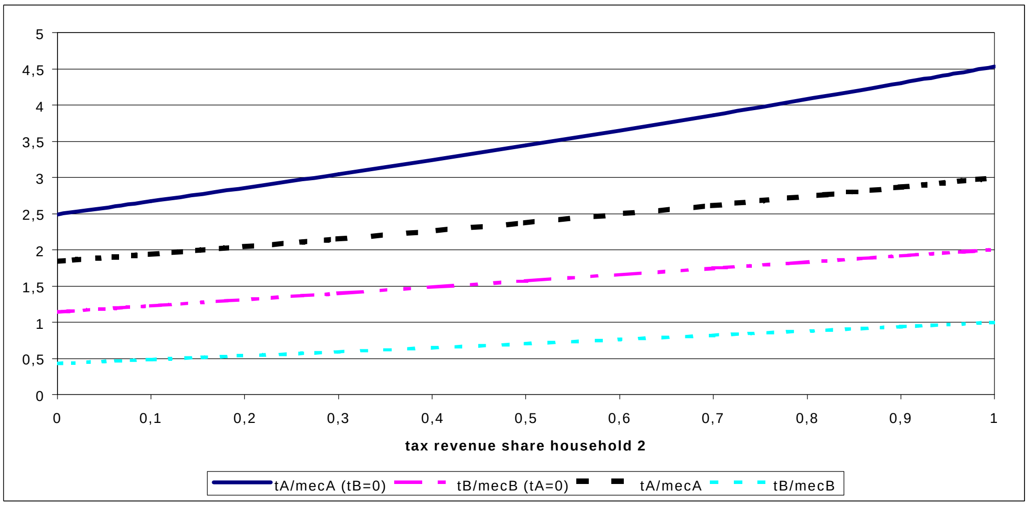


Figure 4.3 Taxes / marginal external congestion costs, with full and partial network pricing



10 The * sign indicates that a tax is optimised.

4.3 Example 2: network interactions in a 3 link network

Example 2 highlights the impact of link tax restrictions on the effectiveness of network congestion pricing. The network, see figure 4.4, consists of three directed links (*a,b,c*) and three nodes (1,2,3). It is a stylised representation of high capacity roads which are used for through traffic in Namur, during the morning peak. *Links a and b* are west of the city centre, *link c* is to the east. The idea is to test partial pricing schemes, that is: taxes on (combinations of) *links a, b and c*. The relative efficiency of the different combinations is compared to the full optimum solution in which all links are priced. As mentioned, it will be assumed that households are compensated for the congestion taxes that they incur (conform equation (3.8)). We start by analysing a central scenario in section 4.3.1, comparing partial pricing schemes and optimal parking charges. Section 4.3.2 takes the same preference structure and analyses the impact of variations in cost characteristics. Section 4.3.3 looks at variations in the preference structure, for the cost structure on the network as defined in the central scenario.

4.3.1 The central scenario

Table 4.3 gives the central scenario reference demands from the representative consumer at each trip origin, for the three origin-destination pairs and the cost function parameters for the three links. For trips from node 1 to node 3, *paths ab and c* can be chosen. In the reference equilibrium *link c* is under-used from the social point of view (see below). With respect to the structure of preferences, we assume that there is no substitution between destinations 2 and 3 for households travelling through node 1. The paths from node 1 to node 3 (*ab and c*) are perceived as perfect substitutes. Conform to the Wardropian network equilibrium condition (see equation (3.5)), the sum of link travel costs on *a and b* is equal to the cost on *link c*.

We first discuss the effects of partial link pricing schemes. Next, the effects of optimal parking taxes at one or both destinations are presented.

The main results from the partial pricing combinations are summarised in table 4.4. The maximal welfare gain is obtained by taxing all network links (*a, b, c*) at approximately marginal external cost. The impact of Mirrlees inequality on optimal prices is small because of the assumption of exact compensation, and because of the presence of alternative paths for traffic going from node 1 to node 3 (network interaction). The optimal prices reduce demand by approximately 6% for all origin-destination pairs, and increase the share of *link c* for trips from node 1 to node 3 from 14.5% to 18%. Optimal pricing on all links achieves efficiency in terms of demand levels as well as in terms of network assignment (distribution of flows over the network), if combined with exact compensation of households through the tax redistribution mechanism. The results suggest that the contribution of demand reduction to the welfare improvement is larger than that of improving the assignment, however. This finding is confirmed within other (larger) network configurations, which are not reported here.

Figure 4.4 Topology for network example 2

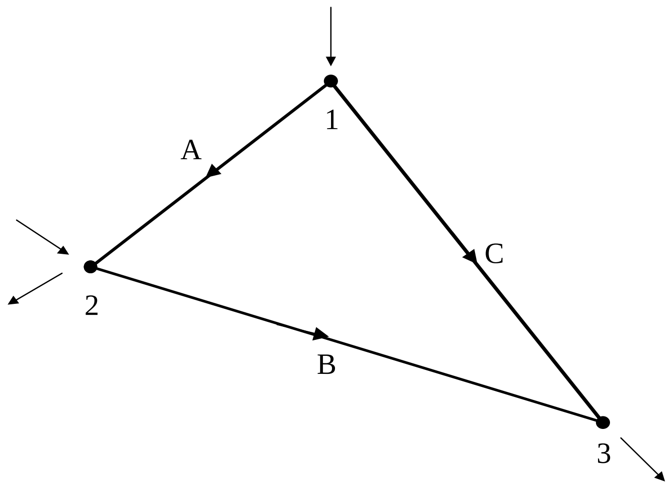


Table 4.3 Cost and demand characteristics of the three link network (reference equilibrium)

Aggregate demand (trips)

1 – 2	993
1 – 3	1590
2 – 3	1089

Costs (Eurocent) and flow (vehicles)

	Intercept	Slope	Flow	Link travel cost
Link a	57	0.004	2353	66.4
Link b	83	0.007	2449	100.1
Link c	150	0.072	230	166.5

Table 4.4 The effects of partial pricing in the three link network

	Reference	Optimal tax on link(s)						
		a, b, c	a	b	c	a, b	a, c	b, c
(1) percentage of maximal welfare gain								
	0	100	46.6	53.9	0	54.4	72.8	92.1
(2) percentage demand change per origin-destination pair								
1,2	0	-5.6	-2.5	-1.5	0	-1.8	-5.8	-4.0
1,3	0	-5.6	-2.5	-1.5	0	-1.8	-5.7	-4.2
2,3	0	-6.3	0.4	-3.6	0	-2.8	0.4	-8.7
(3) ratio of taxes over marginal external costs per link								
A	0	1.005	0.93	0	0	0.21	2.1	0
B	0	0.998	0	0.55	0	0.45	0	1.4
C	0	0.999	0	0	0	0	0.7	0.9
(4) distribution of demand for 1,3 over paths								
AB	85.5	82.0	79.2	78.9	85.5	78.7	81.8	82.2
C	14.5	18.0	20.8	21.1	14.5	21.3	18.2	17.8

The share of the maximal welfare improvement which is achieved by partial pricing schemes ranges from 0% (*link c*) to 92% (*links b and c*). A tax on *link c* will shift traffic going from node 1 to node 3, to *path ab,* which is not desirable in terms of assignment. This negative effect can not be compensated strongly enough by a demand reduction (as paths are perfect substitutes), so that it is optimal to set the tax on *link c* equal to zero if no other links can be taxed. On the contrary, taxes on *links a* and *b* simultaneously improve the assignment and affect demand levels. They permit substantial positive welfare gains. The tax on *link b* performs better than the tax on *link a* because it affects traffic originating from both nodes 1 and 2, on the link suffering from the strongest congestion problem (i.e. *link b*). Note that taxes for one link pricing schemes are below marginal external costs and that the demand reductions are both smaller and more diverse than for complete network pricing. There even is a small demand increase from node 2 to node 3 when only *link a* is taxed. Furthermore, the network assignment is shifted towards over-usage of *link c*, instead of under-usage in the reference equilibrium (always from the socially optimal point of view). Referring to equation (3.14), the example confirms that the second term on the right hand side is usually negative and large, such that taxes are substantially lower than marginal external congestion costs.

With respect to two-link pricing schemes, it is interesting to note that the welfare gain of a combined tax on the serial *links a and b* is much smaller than the sum of the welfare gains of a single tax on *links a* and *b*. The reverse holds for parallel links: the welfare gain of a combined tax on *links a and c* (*b and c*) is much larger than the sum of the gains from single taxes on *a* and *c* (*b* and *c*). Taxing a sequence of links does not outperform taxing one link in the sequence by a lot (compare the gains from scheme *ab* and scheme *b*), when the network interactions for both types of taxes are similar. On the contrary, taxation of parallel links allows to –imperfectly- control assignment choices and demand levels, allowing much larger welfare gains. For the same reasons, it is not surprising that taxes may rise above external costs in two-link pricing schemes, at least in a three link example. For schemes *ac* (*bc*), the tax on *link a* (*b*) is used to –imperfectly- control traffic on the sequence *ab*.

While link taxes are generally thought of as being expensive to implement, parking charges at trip destinations may be a cheaper policy instrument. The example allows to compare the welfare effects of parking taxes at destination 2 and/or destination 3, to the effects of link taxation. Note that *optimal* parking charges, given policy constraints, have been computed. Also, in the present context parking charges are used to internalise congestion externalities, but not to correct for inefficiencies related to parking as such.

Intuitively it is clear that the effectiveness of parking charges depends on the contribution of excess transport demand levels and of inefficient assignment to the global transport inefficiency problem, as parking charges can not correct assignment inefficiencies but they can be used to restrain demand. Since the problem of excess demand in this example (as well as in other network configurations) is more important than the assignment inefficiencies, it is not surprising that an optimal parking charge at both trip destinations realises only 14% less welfare gains than optimal congestion taxes on all network links. An optimal parking charge at destination 2 only, produces 58% of the maximal welfare gain (67% of the gain of optimally charging for parking at both destinations). Similarly, an optimal parking charge at destination 3 only, produces 79% of the maximal welfare gain (92% of the gain of optimally charging for parking at both destinations). In other words, optimal parking charges outperform all one-link pricing schemes, and their performance is comparable to that of two-link pricing schemes.[11] The impact of parking charges on trip demand levels and on assignment is summarised in table 4.5.

Table 4.5 Effect of optimal parking charges on trip demand levels and on path shares, In comparison with first best link taxes

	Reference	First best link taxes	Optimal parking charge at		
			All destinations	Destination 2	Destination 3
(1) Percentage demand change with respect to reference equilibrium					
1,2	0	-5.6	-5.6	-5.8	-4.1
1,3	0	-5.6	-5.5	-5.3	-4.2
2,3	0	-6.3	-6.6	0.2	-8.6
(2) Distribution of demand for 1,3 over paths					
AB	85.5	82.0	86.1	85.6	86.1
C	14.5	18.0	13.9	14.4	13.9

An optimal parking charge at both destinations achieves virtually the same demand reductions as optimal congestion taxes on all links. As could be expected, demand reductions are lower for destinations where no parking charge is implemented. Demand for destination 3 increases slightly when only destination 2 is subject to the charge, which is the consequence of reduced congestion on *path ab*. The network assignment is not improved by parking charges, as there is a switch to the over-used path (*ab*) in all parking scenarios. Because of the demand reduction, the costs of the assignment inefficiency are reduced however. In sum, the decreased performance of parking taxes (minus 14% compared to optimal link taxes) gives an idea of the contribution of assignment inefficiencies to the overall transport inefficiences.

4.3.2 Cost variations

The impact of cost characteristics is analysed for the preference structure of the central scenario, i.e. there are representative households at two locations (nodes 1 and 2), who travel to two destinations (nodes 2 and 3), where substitutability between destinations is excluded. For trips from node 1 to node 3, two paths are available (*path ab* and *path c*). We consider the effect of altering the cost function for *link c* in two ways, keeping the cost functions for *links a* and *b* constant. First, the effect of increasing the slope of *link c* is assessed (case 1). As the slope increases, the link becomes more congestible and hence more expensive from the private and in terms of marginal external congestion costs. Second, the intercept of *link c* is increased (case 2). This can be interpreted as increasing the length of the link, which increases the private costs of using *link c* without directly affecting marginal external congestion costs. The impact of these experiments on the performance of one link pricing schemes is summarised in figure 4.5. Scenarios to the left of the central scenario concern case 1 (changing slope of *link c*), where the slope is lowest for scenario s1. The scenarios to the right concern case 2 (changing length of *link c*), where the length is the smallest for s9.[12]

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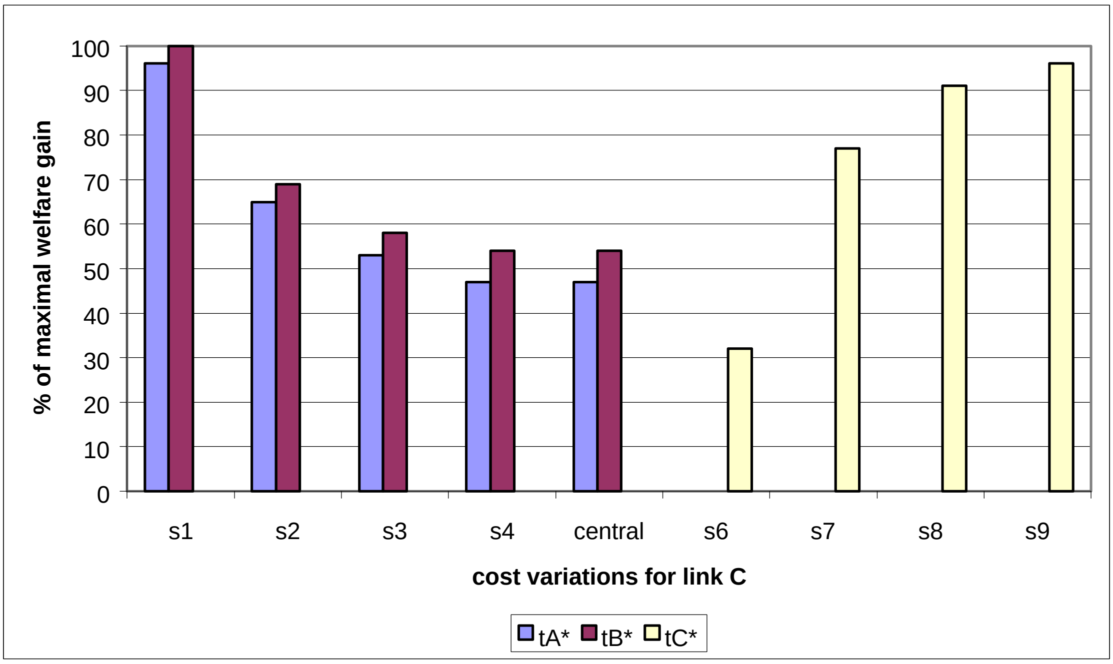
[11] It should be noted that the relative performance of parking charges will decrease in a network with more variation in origins, destinations and trip distances. Furthermore, parking charges do not deter through traffic (e.g. Glazer and Niskanen, 1992).

[12] Each scenario halves the slope (scenario 4 to scenario 1) of link C, or halves the length of link C (scenario 6 to 9) with respect to the previous case.

Figure 4.5 Share of maximal welfare gain from optimal one-link pricing schemes under cost variations



As can be observed, the performance of pricing *link a* or *link b* increases as the slope of *link c* decreases (scenarios 1 to 5). When the slope of *link c* is very low (scenario 1), a tax on *link b* is sufficient to generate the maximal possible welfare gain. It is not possible to realise welfare gains by taxing *link c*, unless its length decreases (scenarios 6 to 9). In those cases where the optimal tax on *link c* is positive, the optimal tax on *links a and b* is zero. These results can not be explained by considering the cost structure of the network alone. Account must be taken of the social valuation of the network assignment in case no taxes are introduced. In other words, the degree of inefficiency of users decisions –which depends on the network cost structure- should be considered. This is discussed in the next paragraphs.

Figures 4.6 and 4.7 show the index of relative efficiency of partial pricing schemes, as well as of 'network heterogeneity'. The latter concept is based on two standard solutions of the network assignment problem in transportation science, the user equilibrium and the system optimum. The user equilibrium follows from uncoordinated cost minimisation by individual users. The resulting network assignment is consistent with the Wardropian version of the consumer equilibrium conditions described in equation (3.5)**,** if the demand levels from the consumer optimisation are used. The system optimum minimises costs from the social point of view, for given demand levels. It corresponds to a command and control assignment procedure. The amount of network heterogeneity indicates to which extent the user equilibrium assignment deviates from the system optimum assignment, for the reference demand levels. Since demand levels are fixed at the reference levels, and since assignment choices are limited to the choice between *paths ab and c* for trips from node 1 to node 3, the amount of network heterogeneity in our example can be described by the deviation between the user equilibrium share of traffic from node 1 to node 3 on *link c*. Figures 4.6 and 4.7 show an index of this deviation.

The figures indicate that heterogeneity drops as the cost of *link c* is increased, either because of an increase in the slope or the intercept. In the case of figure 4.6, the user equilibrium flow on *link c* is too low as compared to the system optimum, and the difference decreases as the slope of *link c* rises. For figure 4.7, the user equilibrium flow on *link c* is too high, from the social point of view for low link lengths. Hence the direction of the assignment inefficiency is reversed between both figures.

In case 1 (figure 4.6) taxing *links a or b* is becomes less efficient when the slope of *link c* rises. This is intuitively straightforward: as *link c* becomes more congestible, it becomes less attractive to tax *links a* and *b*, because this generates excessive congestion on *link c*. If *link c* is not strongly congestible, taxing *link a* is a good way to decrease demand from origin 1, and taxing *link b* tackles demand from both origins (hence the difference in relative efficiency between taxing *link a* and *link b*). Using these instruments generates a limited amount of inefficient assignment only. The efficiency cost of inefficient assignment rises as the slope of *c* rises, however. At first sight, it is remarkable that taxing *link c* only generates no efficiency gains in this network, even if its slope is high. The reason is that the high slope as such leads to a user equilibrium in which *link c* is under-used: the user equilibrium is concordant with the system optimum to a substantial degree. A non-negative tax can not correct for the remaining inefficiency.

In case 2 (figure 4.7) only taxing *link c* generates efficiency gains if only one link in the network can be taxed. This again follows from the direction of network heterogeneity (under-usage of *path ab* from the social point of view). Taxing *link c* only becomes less effective as the length of *c* increases, because the increase in user costs caused by the length increase brings the user equilibrium closer the social optimum, irrespective of whether a corrective tax is used or not. This also explains while the effectiveness drops to zero when the direction of heterogeneity switches sign.

It is interesting that the relative efficiency of partial pricing schemes depends on network heterogeneity, which in turn depends on the cost structure of the network. Partial pricing schemes become less effective as networks become less heterogenous (more homogenous). The reason is that in homogeneous networks, path switching –when possible- is not strongly discouraged through cost function differences between paths. This makes partial pricing schemes a bad instrument for aggregate demand reduction. Unfortunately, demand reduction is the main objective of network pricing in a homogenous network, as assignment becomes more efficient as homogeneity increases.[13] Partial pricing therefore is useful only in strongly heterogenous networks. Of course, full network pricing does not suffer from this problem, as it simultaneously affects trip demand levels and assignment inefficiencies.

The present discussion is relevant to the policy problem in which a (number of) links on which a tax will be introduced, must be selected from a network. In a homogenous network, the choice of a link does not matter much. Taxing any link will generate only modest welfare gains anyway. The discussion of parking charges in section 4.3.1 suggests that other instruments than link taxes should be considered to obtain the desired demand effects. In a heterogenous network, the choice of a link becomes very important. Those links that are over-used from the social point of view should be taxed. These are not necessarily the links with the highest congestion, however (see figure 4.6). It is necessary to compare the fixed demand user equilibrium and system optimum. This however is a relatively simple computation, available from most standard network equilibrium software.

[13] This suggests that uniform pricing schemes become relatively attractive in homogenous networks.

Figure 4.6 **Index of relative efficiency of one-link-pricing for increasing congestibility of link C**

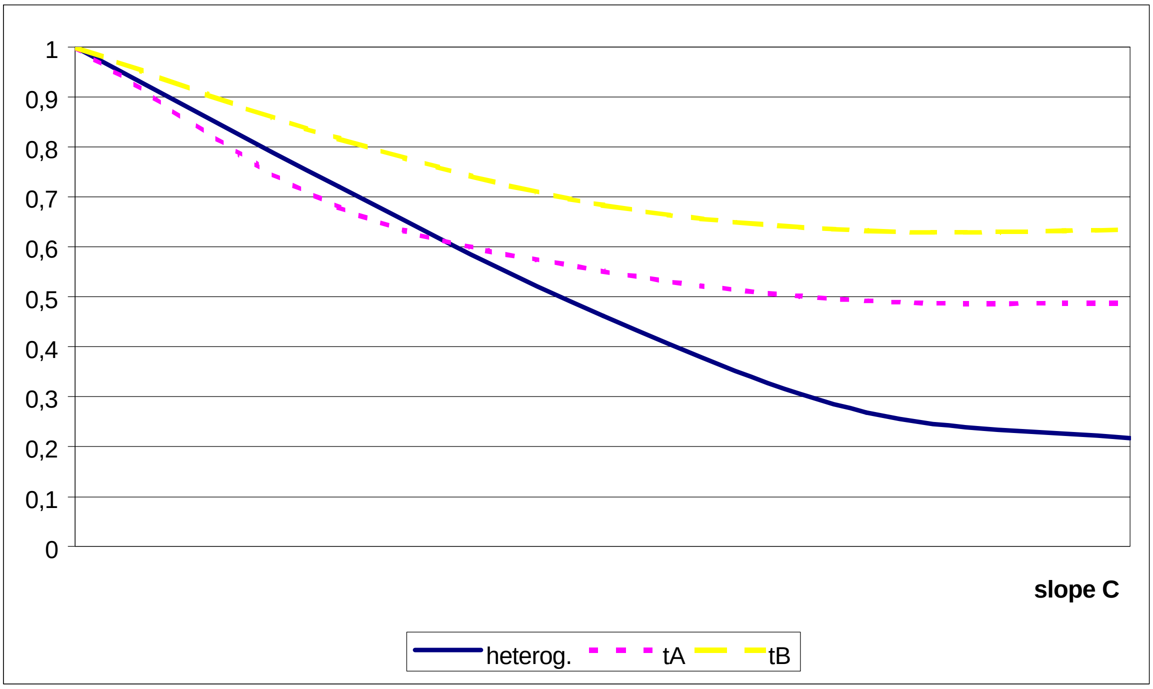
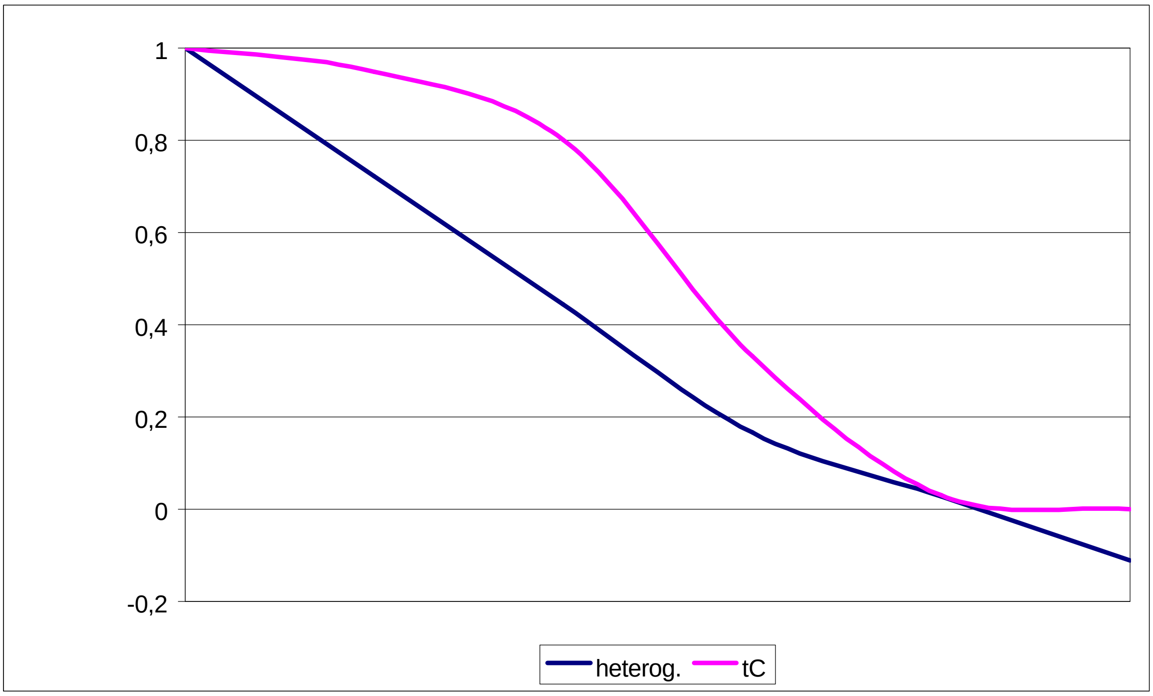


Figure 4.7 **Index of relative efficiency of one-link-pricing for increasing length of link C**



4.3.2 Preference variations[14]

This section presents results concerning the impact of variations in the preference structure on the effects of partial network pricing schemes, while retaining the cost structure of the central scenario. The scenarios are summarised in table 4.3. First, a scenario is considered in which substitutability between destinations (for households travelling through node 1) is positive, in contrast to zero as in the central scenario ('substitute destinations'). Destinations may be substitutes in the long run, independent of trip motives. In the short run, subsitutability can be substantial for shopping destinations. Second, the substitutability between *paths ab* and *c* (for households travelling from node 1 to node 3) is decreased ('imperfect substitute paths'). This may be interpreted as paths representing different transport modes. The congestion functions are left unchanged however.

Table 4.4 Effect of preference variations on the effectiveness of partial pricing systems (% of maximal welfare gain)

	Optimal tax on links:						
	a, b, c	a	b	c	a,b	a,c	b,c
Central scenario	100	46.6	53.9	0	54.4	72.8	92.1
Substitute destinations	100	45.0	53.6	0	54.4	67.5	89.4
Imperfect substitute paths	100	46.6	53.9	0	54.4	72.8	92.1

Table 4.5 Effect of preference variations on the demand impacts of partial pricing systems (% demand change with respect to reference equilibrium)

	Optimal tax on links:						
	a, b, c	a	b	c	a,b	a,c	b,c
Central scenario							
1,2	-5.6	-2.5	-1.5	0	-1.8	-5.8	-4.0
1,3	-5.6	-2.5	-1.5	0	-1.8	-5.7	-4.2
2,3	-6.3	0.4	-3.6	0	-2.8	0.4	-8.7
Substitute destinations							
1,2	-5.5	-3.4	-0.7	0	-1.5	-7.2	-2.1
1,3	-5.7	-2.1	-1.7	0	-1.9	-4.8	-4.4
2,3	-6.3	0.4	-3.5	0	-2.7	0.4	-8.4
Imperfect substitute paths							
1,2	-5.6	-2.5	-1.5	0	-1.8	-5.8	-4.0
1,3	-5.6	-2.5	-1.5	0	-1.8	-5.7	-4.2
2,3	-6.3	0.4	-3.6	0	-2.8	0.4	-8.7

The absolute welfare gains in first-best are equal in all three scenarios. As can be read from table 4.3, the effect of allowing substitution between destinations on the performance of partial pricing schemes is negative, but limited. Table 4.5 indicates that, when destinations are substitutes, demand will react in order to avoid the link taxes. E.g., when *link b* is taxed the demand decrease for destination 2 (for

[14] Other scenarios than the ones discussed here have been tested, but are left out for reasons of brevity. One of these scenarios suggests that consideration of different trip motives (leisure related transport and commuting) may be important: congestion for commuters can cheaply be decreased by a tax which is sufficiently high to keep leisure related trips off the network during the peak period. This scenario merits more detailed analysis (cfr Parry and Bento, 1999, for a non-spatial analysis of the interaction).

travellers going through node 1) is much smaller in the ‘substitute destinations’ scenario than in the central scenario, while the demand decrease for destination 3 is larger. This can be interpreted as saying that in a long run perspective –in which locations of trip destinations become endogenous- partial pricing schemes have undesirable side-effects in terms of locational patterns. Transport and trip destinations will shift to untaxed parts of the network. The first-best pricing system does not suffer from this problem.

Decreased substitutability between paths has no impact on the effectiveness of partial systems, nor on the demand reactions. This is not a general result, as other cost configurations show that decreased substitutability between paths tends to increase the welfare potential of partial pricing schemes. The reason for this is that limited substitution between paths allows the social planner to reduce demand for a given path (mode) without large re-assignment effects to other paths (modes). The fact that this phenomenon does not appear in this network example is due to the cost structure, which is such that users’ assignment decisions are driven by the relative congestion conditions on different paths (modes), and not by their preference over different paths (modes).

5. Concluding comments

We have presented optimal link tax rules for a general static transport network used by households whose residential location is fixed. First, the impact of the impossibility to tax all network links on the remaining link taxes was discussed, for an economy in which individualised lump sum transfers are available. Both the theoretical analysis and the empirical illustrations indicate that in such a case link taxes will deviate strongly from marginal external congestion costs on the link, because of network interactions. In most circumstances taxes will be much lower than marginal external congestion costs.

Second, when optimal individualised lump sum transfers are not possible but congestion tax revenues are redistributed to households according to given shares, the optimal link taxes are influenced by Mirrlees inequality. This concept refers to the tendency of the optimal tax structure to favour households with relatively lower transport costs. It was shown, theoretically and by means of an illustration, that optimal link taxes will deviate from marginal external congestion costs, even in the absence of link pricing constraints.

The analysis shows that the welfare potential of partial pricing systems strongly depends on the characteristics of the no-tax network assignment, and on the particular links which are taxed. In general, partial pricing systems are less performant when the network is less heterogenous. Heterogeneity here refers to the deviation between the user equilibrium and the system optimum. This is so because partial systems have important negative effects on the assignment in a more homogenous network, and their ability to reduce demand is limited. A further suggestion is that the contribution of improved network assignment to transport efficiency is smaller than that of restraining demand. The fundamental reason is that the user assignment and the cost minimising assignment are similar to a substantial degree, certainly in homogenous networks. When the network is homogenous, alternative instruments (e.g. parking charges) should be considered instead of partial link pricing schemes.

The model can be used for alternative applications. One of these is the economic assessment of link capacity changes, most notably capacity reductions. Capacity reductions are politically attractive. The assessment of such policies requires a network approach. They could be welfare improving in case networks contain (an economic version of) the well-known Braess paradox. A second, obvious and important application of the present analysis concerns the problem of link selection. The analysis has concentrated on the description of optimal link taxes in case not all links can be taxed. Alternatively, one could ask which links should be selected for taxation, given that only a limited number of links can be taxed (cfr Verhoef, 2000).

Finally, we mention two caveats. First, transport has been modelled as a direct argument of utility instead of as a derived demand. While this is standard practice, it involves some limitations. The most important one is that the complementarity between labour supply and commuting transport is not made explicit. This also implies that interactions between labour tax distortions and transport taxes are abstracted from. Nevertheless, the same basic interactions as in the present analysis would show up in a model taking the complementarity into account. Second, the assumption of fixed location rules out compensating reactions to transport cost changes in the land market. While this clearly is a simplification, it will again be the case that the same type of interactions appear in a model with a land market.

References

Arnott R., Riley J.G. (1977), Asymmetrical production possibilities, the social gains from inequality and the optimum town, *Scandinavian Journal of Economics*, 79, 301-311

Arnott R., de Palma A., Lindsey R. (1998) Recent developments in the bottleneck model, in Button K., Verhoef E. (eds) (1998), *Road pricing, traffic congestion and the environment. Issues of efficiency and social feasibility*, Edward Elgar, Massachussets, 79-112

Braid R.M., (1996) Peak-load pricing of a transportation route with an unpriced substitute, *Journal of Urban Economics*, 40, 2, 179-197

Brooke A., Kendrick D., Meeraus A. (1996) *GAMS release 2.25 – A user's guide*, GAMS Development Corporation, Washington D.C.

Calthrop E., Proost S., Van Dender K. (2000) Parking policies and road pricing, *Urban Studies*, 37, 1, 63-76

de Palma A., Lindsey R. (2000) Private toll roads:competition under various ownership regimes , *Annals of Regional Science*, 34, 1, 13-35

Else P.K. (1986) No entry for congestion taxes?, *Transportation Research*, 20A, 2, 99-107

Ferris M.C., Kanzow C. (2000) Complementarity and related problems: a survey, in Pardalos P.M., Resende M.G.C. (eds) *Handbook of Applied Optimization*, Oxford U.P., forthcoming

Fujita M. (1990) *Urban economic theory: land use and city size*, Cambridge University Press, Cambridge, 366p.

Glazer A., Niskanen E. (1992) Parking fees and congestion, *Regional Science and Urban Economics*, 22, 1, 123-132

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

Labbé M., Marcotte P., Savard G. (1998) A bilevel model of taxation and its application to optimal highway pricing, *Management Science*, 44, 1595-1607

Larsson T., Patriksson M. (1998) Side constrained traffic equilibrium models - Traffic management through link tolls, in Marcotte P., Nguyen S. (eds) (1998) *Equilibrium and advanced transportation modelling*, Kluwer Academic Publishers, Boston, 125-152

Liu L.N., McDonald J.F. (1999) Economic efficiency of second-best congestion pricing schemes in urban highway systems, *Transportation Research Part B*, 33, 157-188

Marchand M. (1968) A note on optimal tolls in an imperfect environment, *Econometrica*, 36, 575-581

McDonald J.F. (1995) Urban highway congestion: an analysis of second-best tolls, *Transportation*, 22, 353-369

Mirrlees J.A. (1972), The optimum town, *The Swedish Journal of Economics*, 74, 1, 114-135

Parry I., Bento A. (1999) Revenue recycling and the welfare effects of road pricing, *Resources for the Future Discussion Paper*, 99-45

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

Proost S., Van Dender K. (2000) The welfare impacts of alternative policies to address atmospheric pollution in urban road transport, *Regional Science and Urban Economics*, forthcoming

Sheffi Y. (1985) *Urban Transportation Networks – Equilibrium Analysis with Mathematical Programming Methods*, Prentice-Hall, Englewood Cliffs

Small K. (1992) *Urban Transportation Economics,* Harwood Academic Publishers, Chur

Small K., Yan J. (2001) The value of 'value pricing' of roads: second-best pricing and product differentiation, *Journal of Urban Economics*, forthcoming

Straszheim M. (1987) The theory of urban residential location, in Mills E.S. (ed.) *Handbook of Regional and Urban Economics*, volume 2: Urban Economics, 717-758

Verhoef E.T. (1998) *Second best congestion pricing in general static transportation networks with elastic demands*, Discussion paper TI 98-086/3, Tinbergen Institute, Amsterdam-Rotterdam

Verhoef E.T. (2000) *Second-best congestion pricing in general networks: algorithms for finding second-best optimal toll levels and toll points*, Discussion paper TI 2000-084/3, Tinbergen Institute, Amsterdam-Rotterdam

Verhoef E.T., Nijkamp P., Rietveld P. (1996) Second-best congestion pricing: the case of an untolled alternative, *Journal of Urban Economics*, 40, 3, 279-302

Verhoef E.T., Small K.A. (1999) *Second-best congestion pricing with heterogeneity under public and private ownership*, Paper presented at the Helsinki Workshop on The Politics of Pricing, 19-20 August 1999, Helsinki

Wardrop J. (1952) *Some theoretical aspects of road traffic research*, Proceedings of the Institute of Civil Engineers, 1, 2, 325-378

Appendix 1 Mirrlees inequality with income compensation and with price compensation

The analysis of the effect of transport cost differences on the social welfare optimisation in this paper is based on the assumption that in the no intervention equilibrium, the household incomes differ such that household utilities are equal. The price of the composite commodity *x* is equal for households at all locations. We retain the spatial structure of figure 3.1, that is a 2 link serial network connecting the trip destination *D* to the location of households 1 and household 2. Household 2 faces a lower transport cost than household 1. All goods are normal. Graph A.1 shows that this implies a higher marginal utility of income for the household with lower transport costs. While the income compensation is such that $U1^0=U2^0$, an equal income increase for both households leads to a bigger utility increase for household 2, such that $U1^1<U2^1$. An alternative assumption is that the incomes of both households are equal in the no intervention equilibrium, but that the price of the composite commodity adapts such that household utilities are equal across locations. This could be interpreted as the impact of compensating land rents on the price of the composite commodity. In that case, as shown by graph A.2, the marginal utility of income is higher for household 1. Consequently, while $U1^0=U2^0$, we have $U1^1>U2^1$. While any non-Rawlsian social welfare maximisation will exploit the differences in the marginal utility of income, the direction of the effect depends on the model assumptions. The literature on Mirrlees inequality most often assumes price compensation through the land market, while the present paper assumes income compensation.

Figure A.1 Marginal utilities of income with transport cost differences and income compensation

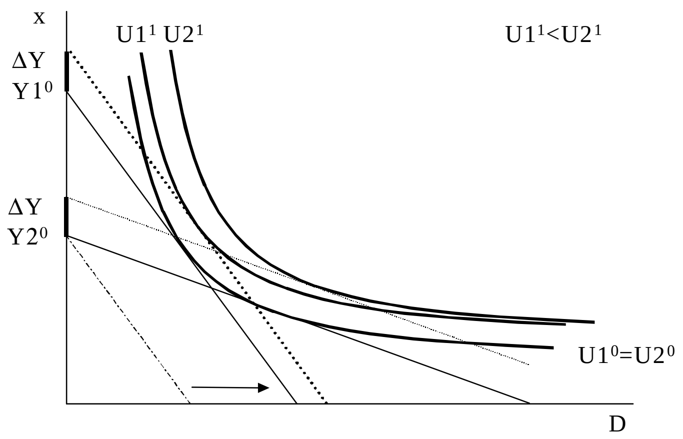
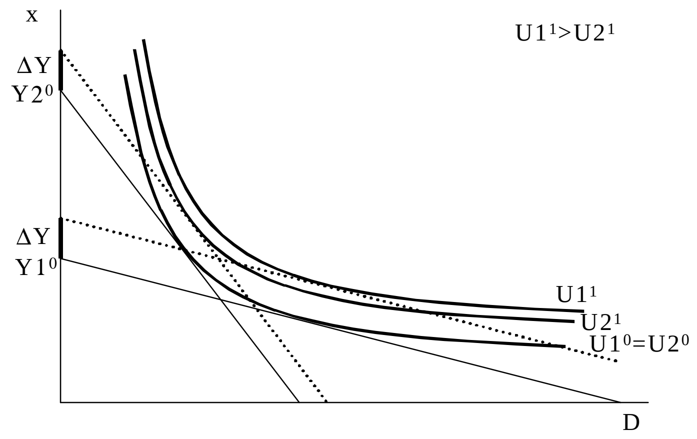


Figure A.2 Marginal utilities of income with transport cost differences and price compensation



Appendix 2 Construction of the network examples

The data are for the examples in section 4.2 and 4.3 obtained from a network model (Toint et al., 19??) for the city of Namur (Belgium) and from the TRENEN model (Proost and Van Dender, 2000). Namur is a regional centre with ca. 100,000 inhabitants, located 50km south-east of Brussels. During the morning peak (1.5 hour length), some 26,000 car trips make use of the Namur road network (data for 1990). 51% of these are through trips, of which the origin and the final destination are outside the Namur area. In the examples, only those through trips are considered which enter the Namur area from the north and the west entry points and which exit the area at the south-east exit points. These trips represent 31% of all through traffic, or 16% of total traffic during the morning peak. The implicit assumption is that demand and route choice for all other trips is fixed. The parameters of the link time cost functions are adapted, so that capacity roughly reflects the fixed demands for the other trips. Furthermore, linear approximations to the link cost functions, at the reference link loads, are used. Monetary cost components other than tolls are taken to be independent of congestion. They are fixed at 0.22 Euro per kilometre, so that on the per trip level they depend on route choice. Time units are converted to time costs by using a constant value of time of 8 Euro/hour. Prices are in 1990 terms.

Preferences are represented by nested CES utility functions, which are calibrated using information on prices and quantities in the reference equilibrium and on elasticities of substitution. With respect to the reference expenditure shares, we assume that morning peak trips, evening peak trips and other trips each stand for one third of the daily transport distance. A morning peak through trip is taken to be on average 10km long, of which 3km use the Namur network. The remaining 7km are assumed to take place under free flow conditions, which is a reasonable approximation as congestion is concentrated in urban areas. Consequently, the part of the morning peak trip on the Namur network represents roughly one tenth of the daily transport distance. Its share in daily transport costs is higher however, because not all other transport takes place under congested conditions. Assuming that the morning and the evening peak are symmetrical, that other trips benefit from free flow conditions, and that congestion increases the time cost by a factor of 1.38 on average[15], the time costs of the morning peak on the Namur area stand for 13% of daily transport time costs. The share of transport time costs in the daily time budget for consumption (8 hours) is (1.38*(6km/60kmh)+(24km/60kmh))/8h = 12.5%. The share of morning peak travel time on the Namur network in the daily time budget is 1.63%. For the money budget share, we assume that daily transport expenditures represent 15% of average daily expenditures, i.e. the same share as in average yearly expenditures. The morning peak expenditures on the Namur network (i.e. ca 0.66 Euro) equal 1/10 of that share, or 1.5% of total expenditures.

When the value of marginal time savings in transport equals the marginal value of time in other consumption activities, the daily time budget for consumption is valued at 64 Euro. The daily money budget is 0.66Euro/0.015 = 44Euro. The generalised daily budget is 108 Euro, of which the share of transport during the morning peak on the Namur network is 1.58%. It is clear that considering such a small share of total expenditures strongly limits the total welfare potential to be expected from pricing reforms. As our focus is on the relative gains from different instruments, the total gain is of less importance than the choice of a small but realistic example.

[15] Figure derived from the network example used in section 4.3

The Center for Economic Studies (CES) is the research division of the Department of Economics of the Katholieke Universiteit Leuven. The CES research department employs some 100 people. The division Energy, Transport & Environment (ETE) currently consists of about 15 full time researchers. The general aim of ETE is to apply state of the art economic theory to current policy issues at the Flemish, Belgian and European level. An important asset of ETE is its extensive portfolio of numerical partial and general equilibrium models for the assessment of transport, energy and environmental policies.

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