Congestion and tax competition in a parallel network

By

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Abstract

The purpose of this paper is to study tax competition on a parallel road network when different governments have tolling authority on different links of the network. Reflecting many current situations in Europe, each link is used by both local and transit traffic, and transit has a choice of route. Each government maximises the surplus of local users plus total tax revenues in controlling local and transit transport. Three types of tolling systems are considered: (i) toll discrimination between local traffic and transit, (ii) uniform tolls on local and transit transport, (iii) local tolls only. The results suggest that the welfare effects of introducing transit tolls are large, but that differentiation of tolls between local and transit transport as compared to uniform tolls does not yield large welfare differences. Moreover, the welfare effects of coordination between countries are relatively small in comparison with the welfare gains of tolling transit. Numerical application of the model further illustrates the effects of different transit shares and explicitly considers the role of asymmetries between countries. Higher transit shares strongly raise the Nash equilibrium transit toll and slightly decrease local tolls. With asymmetric demands, the welfare gains of introducing differentiated tolling rise strongly for the country with lower local demand.

Keywords: congestion pricing, transit traffic

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1. Introduction

Countries' road networks are usually publicly provided, they are congestible, and they are accessible to local users and to transit transport[1]. In many cases, transit traffic has a choice between different jurisdictions' road networks. For example, there are two main routes from South-Central Europe (Switzerland, Austria, Italy) to the north (Belgium, Netherlands, etc.), one through France, the other via Germany. Or consider the transalpine crossing between Germany and Italy, where Austria and Switzerland compete for transit traffic. In both examples, transit has a choice of routes and it interacts with local traffic in each country.

In these circumstances, how would a local jurisdiction like to price access to its infrastructure?[2] We study this question in a model with two parallel routes that are operated by two countries, for given levels of infrastructure supply. Both local and transit traffic contribute to congestion, and the two countries compete for revenue from transit. Assuming that countries maximise a welfare function consisting of local consumer surplus and tax revenues from local and transit traffic, we study strategic tolling by individual countries under various tolling schemes. First, we assume that local traffic and transit can be tolled separately. Second, we look at the case where only uniform tolls are possible or acceptable. Third, we consider the case where only local traffic can be tolled.

In view of recent innovations in transport taxation within the EU, these three tolling regimes are policy-relevant. New forms of transport pricing instruments include kilometre charges (implemented in Germany since early 2003), tolls (already existing, amongst others, on French motorways), and cordon pricing (London). More sophisticated time-of-day pricing regimes are under consideration. Among others, the case of differentiated tolls is relevant because, when Member States use different tolling instruments for local and transit transport, the implied tax levels will automatically differ. The case of uniform tolls provides an appropriate description when EU member countries use the same pricing instruments, because

[1] To avoid confusion, note that we use the term 'transit' to refer to 'through traffic', i.e., traffic that has its both origin and destination outside the country under consideration.

[2] Although the discussion is set in the context of congestible road infrastructure in two countries, similar issues arise in the public provision of e.g. health, educational and recreational services. In this sense, the ideas studied in this paper are not limited to the transport sector. The key feature of the analysis is that foreign (transit) users are not restricted to a particular jurisdiction but can choose between several, and that jurisdictions compete for revenue from transit.

explicit toll discrimination between local and transit transport contradicts EU regulations. Finally, the case of 'local tolls only' resembles the current situation in many countries, where fuel taxes are the main tolling instrument. High fuel taxes can easily be evaded by transit transport, especially in relatively small countries. Hence, the exclusive use of fuel taxes can be considered as a highly stylized example of tolling local traffic only[3]. It is likely that several countries will be limited to tolling local traffic for quite some time, if only because of the technical difficulties and implementation costs associated with tolling transit.

Our analysis builds on several strands of the recent literature. First, the literature on optimal pricing of road use in the presence of congestion has recently been extended to optimal tolling on simple parallel networks. For example, Braid (1996) and Liu and McDonald (1998) consider models with homogeneous users to study optimal second-best tolls on one link in the network, assuming that other links can not be optimally tolled for technical or political reasons. They suggest that the optimal second-best tolls on one link tend to be low, and could actually be negative. Moreover, the welfare gains from this type of second-best tolls are found to be low. However, more recent research by Small and Yan (2001) and Verhoef and Small (1999) shows that allowing for a heterogeneous population of road users substantially increases the benefits from second best tolls.

Second, a small but growing literature explicitly studies the role of different ownership regimes in models with parallel routes. For example, Verhoef et al. (1996) consider competition between a private road and a free-access road, and compare the second-best optimal tolls with those obtained when both roads are privately owned. De Palma and Lindsey (2000) use a bottleneck model of congestion and compare three types of ownership structure: a private road competing with a free access road, two competing private roads, and competition between a private and a public operator. These papers, however, do not distinguish between transit and local traffic demand and, therefore, do not deal with tax competition for transit by welfare maximising governments.

Third, a few recent studies have looked specifically at tax exporting in the transport sector, within a serial network setting. Levinson (2001) analyses US States' choice of instruments for financing transportation infrastructure. Theory predicts, and an econometric analysis

[3] Of course, there is another clear distinction between local and through traffic that is ignored here, viz., that a lot of local traffic is on other roads than transit traffic; the latter is much more concentrated on the major highways.

confirms, that jurisdictions are more likely to opt for toll-financing instead of e.g. fuel taxes, when the share of non-residential users is large. Tolls become more attractive because they allow price discrimination and tax-exporting. De Borger et al (2003) apply a large-scale numerical optimisation model to study tax exporting behaviour by individual regions in a model with both domestic and international freight transport. However, these models are based on a different network structure, they do not consider transit route choice, and they do not study the properties of reaction functions and the resulting Nash equilibria. Moreover, they do not look at the broad variety of tax instruments dealt with in the current paper.

Finally, in a slightly broader sense, the welfare evaluation of transport tax competition of this paper also complements the few explicit numerical illustrations of the welfare effects of various types of tax competition.[4] An early example is Wildasin (1989), who finds substantial welfare effects of property tax competition in the US. More recently, Sorensen (2000) estimates the welfare gain of tax harmonisation within the EU at less than 1% of GDP. The welfare losses of capital tax competition have also been estimated to be relatively small under some, but not all, scenarios considered by Parry (2003). Finally, Sinn (2003) discusses various forms of 'systems competition', referring in general to competition between countries for mobile factors, e.g. within the EU, or on a global scale. He finds the welfare effects to be detrimental in some, but not all, cases.

The contributions of this paper can be summarised as follows. At the theoretical level, it fills two gaps in the literature. First, although competition between operators has been considered before (see the references given above), a common feature of this work is the absence of transit users that can choose between routes. In contrast, our analysis incorporates route choice for transit, and it focuses on the interaction between local and transit traffic when governments compete for revenue from transit. The distinction between local and transit traffic also allows us to explicitly consider a wider range of tolling instruments compared to the existing literature. Importantly, it allows us to look at the implications of pricing only part of the users (local traffic only), a case that seems especially policy-relevant for the near future within the EU. Second, our analysis focuses on competition in a parallel network between two

[4] Seminal contributions to the tax competition literature include Arnott and Grieson (1981), Mintz and Tulkens (1986), and Kanbur and Keen (1993). For a recent survey, see Wilson (1999).

local welfare-maximising governments. This type of competition seems highly relevant in the context of European transport policy and has not been studied in detail in the literature.

Complementing the theoretical analysis by a stylised numerical illustration furthermore allows us to pin down orders of magnitude for each of the issues analysed. It allows us to shed some light on the welfare effects of introducing various types of tolling instruments, the benefits of toll harmonisation, etc. Moreover, the sensitivity of the results to transit shares, to congestion differences and to demand asymmetries can easily be evaluated. Among others, the numerical results suggest that despite a substantial amount of tax exporting, the efficiency costs of tax exporting are fairly small under most scenarios, confirming recent results obtained by Parry (2003) in a totally different context. Also, the welfare effects of uniform versus differentiated tolls are quite limited. To the contrary, using local tolls only is quite costly in welfare terms.

The structure of the paper is as follows. Section 2 presents the general theoretical model. We specify the characteristics of the network and derive optimal tax rules for a given country (implicitly defining the country's reaction functions) for various types of tolling instruments. In Section 3 we simplify by assuming linear demand and cost functions; this allows us to explicitly analyse the properties of the reaction functions, as well as the resulting Nash equilibria. Section 4 reports on a numerical illustration of the following scenarios: the no-toll equilibrium, Nash with differentiated tolls, Nash with uniform tolls, Nash with local tolls only, a centralised solution with differentiated tolls, and a centralised solution with local tolls only. The role of the share of transit and of demand and congestion asymmetries between countries is evaluated. Section 5 concludes.

2. The theoretical model

In this section we first present the structure of the model and provide an overview of the tolling systems analysed. We then study the optimal behaviour of an individual country for each of the cases considered. Throughout this section we focus on the economically most interesting results; most of the derivations are relegated to appendices.

2.1 Structure of the model and the pricing schemes considered

We consider the simplest possible setup. The network consists of two parallel links, and it is assumed that pricing of each link is the responsibility of a different government. Each link carries local traffic, which cannot change routes, and transit traffic, which can. Link capacities are given and both links are congestible. Both governments are assumed to maximise a welfare function that reflects two concerns, viz. (i) the travel conditions of its local users and the associated welfare, and (ii) total tax revenues on the link it controls. We assume that all traffic flows are uniformly distributed over time and are equal in both directions, allowing us to focus on one representative unit period and one direction.

The combinations of tolling instruments as well as the notation used are summarised in Table 1. Note that differentiated tolls for local and transit demand may seem unrealistic because it runs against the non-discrimination rules in trade agreements. However, some currently used pricing instruments do imply implicit price-discrimination against foreign users.[5] Note that Table 1 only lists the three cases where both countries use the same type of tolling.[6]

Table 1: The tolling systems studied

Description	Tolling instruments	Example
Differentiated tolls for local and transit transport	τ_i : transit toll region i (i=A,B) t_i : toll on local transport in region i (i=A,B)	Eurovignette (favours more intensive local users)
Uniform tolls for local and transit transport	θ_i : uniform toll in region i (i=A,B)	Current tolls on French highways
Tolls on local users only, no transit toll	t_i : toll on local transport in region i (i=A,B)	Fuel taxes, parking charges

[5] Take as an example the yearly lump-sum fee for access to a country's network that is to be paid in Switzerland and in many other countries (the Eurovignette system): this in fact boils down to discrimination in favour of the local users as, almost by definition, they use the network more frequently.

[6] In principle, we could also examine cases where the governments use different types of tolling systems. Indeed, these mixed cases exist in reality: France uses a uniform tolling system for motorways while Belgium and the Netherlands have no explicit toll, so they use a system similar to the case where only local traffic can be tolled. Extending the analysis to the mixed cases is both conceptually and analytically straightforward.

Turning to the specification of the model, demand for local transport in A and B is represented by the strictly downward sloping inverse demand functions $P_A^Y(Y_A)$ and $P_B^Y(Y_B)$, respectively, where Y_A and Y_B are the local flows on both links. The generalised prices $P_i^j(.)$ include resource costs, time costs and tax payments or user charges. Similarly, overall demand for transit traffic is described by the strictly downward sloping inverse demand function $P^X(X)$, where *X* is the total transit traffic flow. We have

$$X_A + X_B = X \ , \qquad (1)$$

where X_A and X_B are the transit flows via A and B, respectively. The two links are assumed to be perfect substitutes: transit users choose the route with the lowest generalised (money plus time) cost but have no specific preferences towards any of the routes.

Turning to the cost side, the generalised user cost for transit via route *A*, denoted g_A^X, equals the sum of the time and resource costs of travel plus the transit toll on *A* [7]:

$$g_A^X = C_A(X_A + Y_A) + \tau_A$$

In this expression, $C_A(.)$ is the time plus resource cost on route *A*, assumed to be strictly increasing in the total traffic volume. Similarly, the generalised user cost for local use of route *A* is given by

$$g_A^Y = C_A(X_A + Y_A) + t_A \, .$$

User costs for route B are defined in an analogous way.

Since we assume perfect substitutability between links for transit, in equilibrium the generalised cost for transit equals the generalised cost on the link with the lowest generalised cost. If both routes are used, transit traffic will be distributed across links so as to equalise generalised costs. Specifically, the Wardrop principle implies that

$$\begin{aligned} P^X(X) = g_A^X &= C_A(X_A + Y_A) + \tau_A \ iff \ X_A > 0 \\ P^X(X) = g_B^X &= C_B(X_B + Y_B) + \tau_B \ iff \ X_B > 0 \end{aligned} \qquad (2)$$

[7] In what follows, we develop all specifications for the case of differentiated tolling; the cases of uniform tolls and local tolls only are easily derived by analogy.

Moreover, equilibrium for local traffic implies

$$P_A^Y(Y_A) = g_A^Y = C_A(X_A + Y_A) + t_A \qquad (3)$$

$$P_B^Y(Y_B) = g_B^Y = C_B(X_B + Y_B) + t_B \qquad (4)$$

Unless otherwise noted, we focus on the case where all types of traffic exist in equilibrium, i.e., there is local and at least some transit in both countries. In theory, of course, this is just one of the many (in fact, sixteen) possibilities that exist. Indeed, when certain taxes are too high or there is too much other traffic using the same road, some types of transport demand may disappear, affecting the structure of the remaining demand functions. This is a well-known problem in the tax competition literature (see Mintz and Tulkens, 1986). However, many of these cases are not very interesting in practice (e.g., cases where there is no local traffic, cases where there is no transit in neither A or B). We therefore largely focus on the most relevant case where both types of transport exist in both countries.

2.2. Optimal tolls in a parallel network: the case of differentiated tolls

Assume each country can set different tolls on local transport and on transit on its territory. To study the optimal tolls set by, say, country A, we use the properties of the reduced-form demand system for the different types of transport in the first-order conditions for welfare optimisation in country A. The reduced-form demand system is obtained by solving the equilibrium conditions (2), (3) and (4); it expresses local and transit demand in both countries as a function of all tax rates.:

$$\begin{matrix} X_A^r[\tau_A, t_A, \tau_B, t_B],\ X_B^r[\tau_A, t_A, \tau_B, t_B] \\ Y_A^r[\tau_A, t_A, \tau_B, t_B],\ Y_B^r[\tau_A, t_A, \tau_B, t_B] \end{matrix} \qquad (5)$$

In Appendix 1 we show that these demand functions have the following properties:

$$\begin{matrix} \frac{\partial X_A^r}{\partial \tau_A} < 0, \frac{\partial X_A^r}{\partial \tau_B} > 0\ \frac{\partial X_A^r}{\partial t_A} > 0, \frac{\partial X_A^r}{\partial t_B} < 0 \\ \frac{\partial Y_A^r}{\partial \tau_A} > 0, \frac{\partial Y_A^r}{\partial \tau_B} < 0\ \frac{\partial Y_A^r}{\partial t_A} < 0, \frac{\partial Y_A^r}{\partial t_B} > 0 \end{matrix} \qquad (6)$$

$$\frac{\partial X_B^r}{\partial \tau_B} < 0, \frac{\partial X_B^r}{\partial \tau_A} > 0 \; \frac{\partial X_B^r}{\partial t_B} > 0, \frac{\partial X_B^r}{\partial t_A} < 0$$
$$\frac{\partial Y_B^r}{\partial \tau_B} > 0, \frac{\partial Y_B^r}{\partial \tau_A} < 0 \; \frac{\partial Y_B^r}{\partial t_B} < 0, \frac{\partial Y_B^r}{\partial t_A} > 0 \quad (7)$$

Increasing local transport taxes in a given country reduces local demand and raises transit; it reduces transit and raises local demand abroad. Higher transit taxes in a country have the opposite effects. Intuitively, any tax change has two effects: first, it affects the distribution of transit over the two routes and, second, by affecting congestion levels in the two regions, it has an impact on the competition in each country between transit traffic and local traffic for the same road space. An example helps to illustrate this. Take the effect of increasing the transit tax in *B* (τ_B). This tax increase will make route *B* less interesting for transit traffic so that X_B goes down, whereas demand for transit on route A rises. However, there are secondary effects. The positive effect on X_A raises congestion in *A* and hence the generalised user cost, whereas the lower volume of transit on route *B* decreases the generalised cost of using route *B*. The changes in congestion mitigate the initial transit effects described before; more importantly, they raises the demand for local traffic in country B and reduce demand for local transport Y_A.

Finally, in Appendix 1 we also show the following useful result on the relative impact of a transit tax and a tax on local transport on the demand for transit:

$$\left|\frac{\partial X_A^r}{\partial \tau_A}\right| > \left|\frac{\partial X_A^r}{\partial t_A}\right|$$

Both taxes have opposite effects, but in absolute value the transit tax has a larger effect on transit demand than an increase in the tax on local traffic. This makes intuitive sense because a higher local tax only affects transit demand indirectly via the induced reduction in congestion. This finding will be useful for the interpretation later.

Using the reduced-form demand system, we proceed to analysing the optimal behaviour of a given country, conditional on the tolls set abroad. We assume that the welfare function used by each of the governments consists of the sum of consumer surplus for the local users plus the total tax revenues earned on local and transit traffic on its territory. Consumer surplus for foreigners is ignored. Consider, therefore, the problem of country *A*:

$$\underset{t_A,\tau_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + t_A Y_A + \tau_A X_A \,, \tag{8}$$

where, see before, $g_A^Y = C_A(X_A + Y_A) + t_A$, and the reduced-form demands for X_A and Y_A depend on all four tax rates, see (5). Moreover, the country takes the tolls t_B, τ_B in country B as given.

The first-order conditions for an interior solution to problem (8) can, using (3) and (4), be written as:

$$\left(t_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial Y_A^r}{\partial t_A} + \left(\tau_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial X_A^r}{\partial t_A} = 0 \,, \tag{9}$$

$$\left(t_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial Y_A^r}{\partial \tau_A} + \left(\tau_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial X_A^r}{\partial \tau_A} + X_A^r = 0 \,, \tag{10}$$

where $V_A = X_A + Y_A$ is the total (local plus transit) traffic volume in country A. Details on the derivation are provided in Appendix 1. There we further show that (9) and (10) imply the following tax rules (analogous results hold for country B):

$$t_A = LMEC_A + X_A \frac{\partial C_A}{\partial V_A} \tag{11}$$

$$\tau_A = LMEC_A + X_A \left[\frac{\left(\frac{\partial C_A}{\partial V_A} - \frac{\partial P_A^Y}{\partial Y_A}\right)\frac{\partial Y_A^r}{\partial t_A}}{\frac{\partial X_A^r}{\partial \tau_A}} \right] \tag{12}$$

$$\tau_A > t_A \,. \tag{13}$$

In these expressions, $LMEC_A$ is the *local* direct marginal external congestion cost, defined as:

$$LMEC_A = Y_A \frac{\partial C_A}{\partial V_A} = Y_A \frac{\partial C_A}{\partial X_A} = Y_A \frac{\partial C_A}{\partial Y_A}$$

It captures the effect of extra traffic on the generalised user cost in country *A*, multiplied by the number of local users of the link. It is a direct marginal external cost in that it does not take into account feedback effects on demand. Note that country *A* does not consider the time losses imposed on transit traffic through *A* as part of the relevant local marginal external cost.

Expressions (11), (12) and (13) imply that the local and transit tolls both exceed the local marginal external cost; moreover, the transit toll is strictly larger than the local toll. Transit taxes higher than taxes on local transport are consistent with the tax competition literature; they simply reflect tax exporting behaviour (see, e.g., Arnott and Grieson (1981), Wilson (1999)). However, that the local toll exceeds LMEC follows from the interaction of local and transit demand in generating congestion. As a consequence, the true opportunity cost of an increase in local traffic not only covers the local direct marginal external cost but also the opportunity cost of the lost tax revenues on transit: more local traffic implies higher congestion and hence less transit demand.[8]

2.3. Optimal tolls in a parallel network: uniform tolls

Suppose countries are limited to uniform tolls, i.e., the toll is restricted to be the same for local and transit trips. Denote the uniform tolls by θ_A and θ_B in regions A and B, respectively, where $\theta_i = \tau_i = t_i \ (i = A, B)$.

Solving the equilibrium conditions (2), (3) and (4) for the case of uniform tolls now yields the system:

$$X_A^r[\theta_A,\theta_B],\ X_B^r[\theta_A,\theta_B],\ Y_A^r[\theta_A,\theta_B],\ Y_B^r[\theta_A,\theta_B] \qquad \text{(5bis)}$$

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[8] Note that, for the specific model structure considered here, it turns out that the local tax equals the *global* direct marginal external cost of a traffic increase in country A, defined as

$$GMEC_A = (Y_A + X_A)\frac{\partial C_A}{\partial V_A} = V_A \frac{\partial C_A}{\partial V_A}.$$

The global marginal external cost is the increase in generalised cost from an extra unit of traffic, multiplied by the total number of road users in *A*. That the local tax exceeds the local marginal external cost is a general result; that it precisely equals the global marginal external cost is an artifact of the model structure. The intuition can be understood by the definition of the generalised cost in combination with the structure of the objective function. Transit traffic is indifferent between paying one Euro more in time costs and one Euro more in transit tolls. The government that hosts the transit traffic obviously prefers the transit toll. Therefore, the opportunity cost of allowing one more unit of local traffic equals the local marginal external cost plus the total transit revenue foregone through the increase in average costs for transit traffic. The definition of generalised costs implies that the increase in average costs (the marginal external cost of the transit traffic) equals the total transit revenue foregone.

In Appendix 2 we show that the reduced-form demand functions for A (analogous results hold for B) have the following properties:

$$\frac{\partial X_A^r}{\partial \theta_A} < 0\,, \frac{\partial X_A^r}{\partial \theta_B} > 0, \frac{\partial Y_A^r}{\partial \theta_A} < 0, \frac{\partial Y_A^r}{\partial \theta_B} < 0$$

Again, an increase in the uniform tax in a region is expected to have a double effect on transit (local) demand in that region: a direct negative effect, and an indirect positive effect due to the lower volume of local (transit) traffic. The above results show that the former effect dominates the indirect feedback effect.[9] We also find that an increase in the uniform tax abroad (e.g. in B) raises transit demand but reduces local demand (e.g., in A). The reason is simply that overall transit demand is shifted from B to A, which in turn raises congestion in A and hence lowers local demand in A.

To determine the optimal uniform toll for country A, consider the problem:

$$\underset{\theta_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + \theta_A (Y_A + X_A)$$

The first-order condition can be written as, after some manipulation (see Appendix 2):

$$\theta_A = Y_A \frac{\partial C_A}{\partial V_A} - \frac{X_A^r}{\dfrac{\partial Y_A^r}{\partial \theta_A} + \dfrac{\partial X_A^r}{\partial \theta_A}}$$

It immediately follows that $\theta_A > LMEC_A$, unless transit in A is zero. The optimal uniform toll exceeds the local direct marginal external cost, and it rises with transit. Again, except for the role of congestion, this is in line with the earlier tax competition literature. Intuitively, the toll balances the distortion on the local transport market and the revenue opportunities from transit.

[9] This is in line with our earlier finding that, in the case of differentiated taxes, in absolute value the effect of the transit tax on the transit flow exceeded that of the tax on local transport.

2.4. Optimal tolls in a parallel network: the case of local tolls only

Suppose the government cannot tax transit ($\tau_i = 0\ (i = A, B)$). The equilibrium conditions (2), (3) and (4) can then be solved for the system of reduced form demand functions that depend on the local tolls in both countries:

$$X_A^r[t_A, t_B],\ X_B^r[t_A, t_B],\ Y_A^r[t_A, t_B],\ Y_B^r[t_A, t_B] \qquad \text{(5ter)}$$

The signs of the derivatives of these demand equations are identical to those of the reduced demand functions of the differentiated toll case. Own price effects are negative, cross price effects positive.

The first-order condition to the problem for country A:

$$\underset{t_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + t_A Y_A$$

implies:

$$t_A = Y_A \frac{\partial C_A}{\partial V_A}\left[1 + \frac{\dfrac{\partial X_A^r}{\partial t_A}}{\dfrac{\partial Y_A^r}{\partial t_A}}\right]$$

where the term between square brackets is shown to be positive (see Appendix 3). Using the signs of the derivatives of the demand functions this implies that the tax is positive but smaller than local marginal external cost:

$$0 < t_A < LMEC_A$$

This result underscores the importance of the interaction between local and transit traffic. To understand the intuition, note that the toll reduces local transport demand, a welfare-raising correction for the externality this traffic imposes. However, the reduction in local traffic reduces the marginal private time cost for transit and attracts more transit; this decreases local welfare and induces a tax below LMEC. If transit traffic reacts very strongly to an average travel time cost decrease, it may be optimal to set the tax very low so as to avoid attracting too much transit. Note that, if the local toll had no affect on transit, a toll equal to LMEC would be optimal.

2.5. Optimal tolls under various tolling systems: summary

Theorem 1 summarises the findings of this section under the maintained assumption that there is both transit and local traffic at the equilibrium.

THEOREM 1

a. Optimal differentiated tolls imply that:

(i) the local and transit tolls both exceed the local marginal external cost: $\tau_i > LMEC_i$**,** $t_i > LMEC_i$**;**
(ii) the transit toll is strictly larger than the local toll: $\tau_i > t_i$**.**

b. The optimal uniform toll ($\theta_i = \tau_i = t_i$**) exceeds the local marginal external cost:** $\theta_i > LMEC_i$**. It will be higher the more important is transit traffic through the country.**

c. If only local traffic can be tolled, the optimal toll is positive but smaller than the local marginal external cost: $0 < t_i < LMEC_i$**.**

These results show that a wide range of optimal tolling schemes is possible. Some of these may well be consistent with observed practice. For example, the use of vignettes in some countries comes close to the idea of tax differentiation, and it indeed implies the potential for tax exporting to foreigners. Our findings may also help explain why small open economies unable to tax transit, favour taxes on local traffic that are substantially below marginal congestion costs. In fact, such countries are often slow to accept congestion taxes or are even explicitly opposed to their introduction, unless transit can also be taxed (Belgium, the Netherlands, etc.). The results presented here for the case 'local tolls only' are consistent with this type of behaviour.

3. Nash equilibria for linear cost and demand functions

The optimal tax rules derived in the previous section under different tolling systems implicitly define countries' reaction functions to taxes abroad. To formally study their properties and to analyse the resulting Nash equilibria, it is instructive to impose more structure on the problem. In this section we therefore focus on linear demand and cost functions. These simplifications also pave the way for the numerical analysis that follows in Section 4.

Specifically, we use the following linear inverse demand functions:

$$\begin{aligned} &P^X(X) = a - bX \\ &P_A^Y(Y_A) = c_A - d_A Y_A \\ &P_B^Y(Y_B) = c_B - d_B Y_B \\ &with\ a, b, c_A, d_A, c_B, d_B > 0 \end{aligned} \qquad (14)$$

Cost functions for transport time (and resources) are specified as:

$$\begin{aligned} &C_A(X_A + Y_A) = \alpha_A + \beta_A(X_A + Y_A) \\ &C_B(X_B + Y_B) = \alpha_B + \beta_B(X_B + Y_B) \\ &with\ \alpha, \beta > 0 \end{aligned} \qquad (15)$$

As before, we only consider the general case where both regions have transit and local transport. The algebraic derivations to arrive at the reaction functions and to show the existence of a Nash equilibrium for the various tolling regimes are conceptually simple, but somewhat tedious. We have therefore delegated the derivations to Appendix 4 and limited the discussion here to the economic implications of our findings.

3.1. Reaction functions and Nash equilibrium: differentiated tolls

The reaction functions for country A (analogous results hold for B) are given by the following linear expressions:

$$\tau_A = c_A^\tau - (\frac{1}{2}\frac{\gamma_2^A}{\gamma_1^A})\tau_B - (\frac{1}{2}\frac{\gamma_4^A}{\gamma_1^A})t_B$$
$$t_A = c_A^t + (\frac{1}{2}\frac{\gamma_2^A}{\gamma_1^A}K^A)\tau_B + (\frac{1}{2}\frac{\gamma_4^A}{\gamma_1^A}K^A)t_B \qquad (16)$$

where the coefficients are explicitly defined in Appendix 4. Here it suffices to note:

$$\gamma_1^A < 0, \gamma_2^A > 0, \gamma_4^A < 0$$

$$\left|\gamma_2^A\right| > \left|\gamma_4^A\right|$$

$$-1 < K^A < 0$$

Interpretation of the signs of the foreign taxes on optimal local taxes in A is then clear. We find that an increase in the transit tax abroad induces country A to optimally adjust both its transit tax and the tax on local traffic upwards, but that the impact on the transit tax is larger than the effect on the local tax. Why is this the case? The higher tax on transit in B reduces transit there and raises transit demand in A. This increases local congestion in A. The optimal response in A is therefore to raise both taxes. Similarly, a higher local tax in B induces country A to optimally reduce transit as well as local taxes in A. The higher tax in B reduces congestion in B, and makes B relatively more – and A relatively less – attractive to transit traffic. This also reduces both congestion and tax revenues in A. To compensate, country A raises its tax rate on local traffic; this reduces congestion but raises tax revenues.

In Appendix 4 we formally show existence of a Nash equilibrium. Explicitly solving for the equilibrium tax rates does not yield extra economic insights. Therefore, to study the properties of the equilibrium in function of a number of crucial parameters describing the tax competition problem (e.g., the size of the country, the importance of transit etc.), we resort to numerical analysis in Section 4 below.

3.2. Reaction functions and Nash equilibrium: uniform tolls

The reaction function for country A as a function of the uniform tax rate in B is given by the linear relation:

$$\theta_A = \frac{c_2^{tuA}}{c_1^{tuA}} + \frac{c_3^{tuA}}{c_1^{tuA}}\theta_B \qquad (17)$$

where (see Appendix 4) $c_1^{tuA} > 0$, $c_2^{tuA} > 0$, $c_3^{tuA} > 0$. An analogous result holds for B. This shows that the reaction functions are upward sloping. A Nash equilibrium can again be shown to exist.

3.3. Reaction functions and Nash equilibrium: local tolls only

The reaction function for country A is:

$$t_A = \frac{c_2^{tlA}}{c_1^{tlA}} + \frac{c_3^{tlA}}{c_1^{tlA}}t_B \qquad (18)$$

where $c_1^{tlA} > 0$, $c_2^{tlA} > 0$, $c_3^{tlA} > 0$.

Again, the slope of the reaction functions is positive, and (assuming both types of traffic exist at the equilibrium) existence of a Nash equilibrium can be shown, see Appendix 4.

4. Numerical illustration

We illustrate the theoretical analysis with a numerical version of the linear model of the previous section. The data represent realistic orders of magnitude for the situations modeled above, but they do not correspond to one particular real-world example. We start the discussion by analysing a central, fully symmetric scenario. Next, we use sensitivity analysis to consider the role of transit, of asymmetric local demand functions (reflecting differences in the relation between local demand and road capacity), and of differences in congestion functions. For each of the scenarios considered, the following equilibria are calculated[10]:

[10] Note that, by construction, we obtain interior solutions for the counterfactual scenarios.

- S1: The no toll equilibrium, to which the model is calibrated;
- S2: Nash equilibrium with differentiated tolls;
- S3: Nash-equilibrium with uniform tolls on local and transit traffic;
- S4: Nash equilibrium with local tolls only;
- S5: Centralized solution with differentiated tolls
- S6: Centralized solution with local tolls only.

In each scenario, the toll revenue is allocated to the tolling countries. The discussion of the results focuses on those insights that are not immediately obvious from the theoretical analysis. Tables containing detailed results are in Appendix 5.

4.1 Central scenario

The central scenario uses a fully symmetric version of the model, with identical congestion and local demand functions for both countries. In addition to symmetry, a 50/50 distribution of transit and local traffic in each country is assumed, in the zero-toll reference situation. The congestion function is a linear approximation to the French functional form for highways (Quinet, 1998, p. 139), at a reasonably congested traffic volume. The parameterization of the cost and demand functions yields reasonable generalized price elasticities, congestion levels and marginal external congestion costs (see below).

Table 2 shows the basic properties of the demand and cost functions, and the associated reference demand and cost levels. Note that transit demand is twice local demand in A or B and it is, endogenously, equally distributed over both countries. The time cost is taken to be 50% of the generalized price. The non-time component is fixed across simulations.

Table 2 Zero-toll symmetric equilibrium (central case parameterization)

	Intercept	Slope	Level	Unit
Local demand, A=B	1690	-5.96	1300	Trips
Transit demand	3380	-11.92	2600	Trips
Time cost function, A=B	1.617	0.012	32.7	Euro/trip
Generalized price, A=B			65.4	Euro/trip
Local MEC, A=B			15.5	Euro/trip
Global MEC, A=B			31.1	Euro/trip

Note: all trips are taken to be 100km long; the trip levels are hourly levels

Table 3 summarizes the results of the central scenario; detailed results for each of the six equilibria are in Tables 1 and 2 of Appendix 5. The optimal tolls illustrate the results of the theoretical analysis. In the Nash equilibrium with differentiated tolls (S2), both the local and global toll exceed the local marginal external cost, the local toll is equal to the global marginal external congestion cost, and the transit toll exceeds the local toll. This contrasts to the centralised solution (S5), where both transit and local tolls equal global marginal external cost. In the Nash equilibrium with uniform tolls (S3), the optimal toll is between the toll levels of the differentiated case. Interestingly, the optimal local toll is very low in the Nash equilibrium case where transit remains un-tolled (S4): it amounts to 6.8 Euro relative to a global marginal external cost of 30.7 Euro.

Concerning the relative welfare levels at the different equilibria, first observe that the Nash equilibrium with differentiated tolls is able to generate a large percentage, more precisely 93%, of the maximal possible welfare gain at the centralised solution S5. Moreover, the shares of both countries and of transit in total welfare are fairly close to that of the centralised solution. In both cases the shares of local traffic in welfare increase substantially compared to the no-toll situation, while that of transit traffic diminishes. Our finding that the Nash equilibrium with differentiated tolls brings us close to the social welfare optimum suggests that the welfare costs of the lack of coordination between countries are relatively modest. Sorensen (2000) and Parry (2003) find a similar result, in totally different contexts. At any rate, tolling with no coordination is much better than no tolling at all.

Table 3 Key results for the central scenario (50% share of transit traffic)

	S1 No tolls	S2 NE – diff.	S3 NE – unif.	S4 NE - local	S5 Centr. – diff.	S6 Centr. – local
Local toll (Euro/trip)	0	27.1	36.8	6.8	27.7	27.5
Transit toll (Euro/trip)	0	37.9	36.8	0	27.7	0
Local MEC (Euro/trip)	15.6	13.9	13.3	15.1	13.8	13.7
Global MEC (Euro/trip)	31.1	27.1	26.5	30.7	27.7	29.4
Share max. W gain (%)	0	93	89	22	100	49
Transit share in total W (%)	50.0	35.2	35.8	50.0	38.9	50.4

Second, comparing the Nash equilibrium with and without toll differentiation (S2 and S3) suggests that the uniformity constraint implies a very small overall welfare loss (0.06%-point), despite a substantial impact on the local toll. This increases from 27.1 Euro/trip to 36.8 Euro/trip, close to the transit toll of 37.9 in the differentiated tolling case. However, this hardly affects welfare compared to the differentiated tolling case. Local welfare goes down only marginally because the reduction in local consumer surplus is almost fully offset by the increase in tax revenues, which have the same welfare weight as consumer surplus. Transit experiences only a modest welfare gain relative to the differentiated tolling case; the reason is that the toll on transit is quite similar under both the uniform and the differentiated tolling case. The results indicate that the overall welfare effects of uniform versus differentiated tolls are quite similar, although the distribution between local and transit welfare, and the composition of local welfare are substantially different. Finally, the uniformity restriction does not protect transit from substantial welfare losses compared to the no toll situation.

Third, consider the cases where transit trips cannot be tolled. These scenarios are of interest because zero tolls on transit traffic mimics current (and possibly future) conditions in Europe, at least for transit countries that are small enough to allow transit to pass without taking fuel. We find the performance of both the Nash and the centralised outcome (S4 and S6) to be substantially worse than in the cases where transit is tolled. The Nash equilibrium without transit tolls (S4) generates only 21.5% of the maximal possible welfare gain (S5) and 23% of the welfare gain in the Nash equilibrium with differentiated tolls (S2). Note also that the centralised solution with zero transit tolls performs worse than the Nash equilibria with and without toll differentiation.

Our findings suggest, therefore, that welfare losses are much more substantial when transit remains un-tolled than when tolls on local and transit transport are required to be uniform. Moreover, it also seems that not tolling transit is equally – if not more – important for welfare than tax competition itself. Moving from the centralised solution with taxes on both local and transit traffic to a centralised situation with no toll on transit (compare S5 and S6), we see that the tax on local traffic only falls marginally below marginal external cost. The large welfare difference is uniquely due to un-tolled transit. Introducing tax competition under the zero transit toll constraint then does introduce an additional welfare loss (compare S6 and S4): countries find it in their best interest to tax local traffic at far less than the global marginal external congestion cost. As countries care about local welfare only, they set local tolls at a low level, so encouraging local trip demand and indirectly discouraging transit trips.

To summarise, our numerical findings so far indicate that:

- It is important to introduce some form of transit tolling; the welfare effects of tolling transit are large.

- The precise type of transit tolling (uniform local and transit tolls versus differentiated transit tolls) has relatively small welfare effects.

- The welfare losses due to not tolling transit seem to be at least as important as the losses due to tax competition itself.

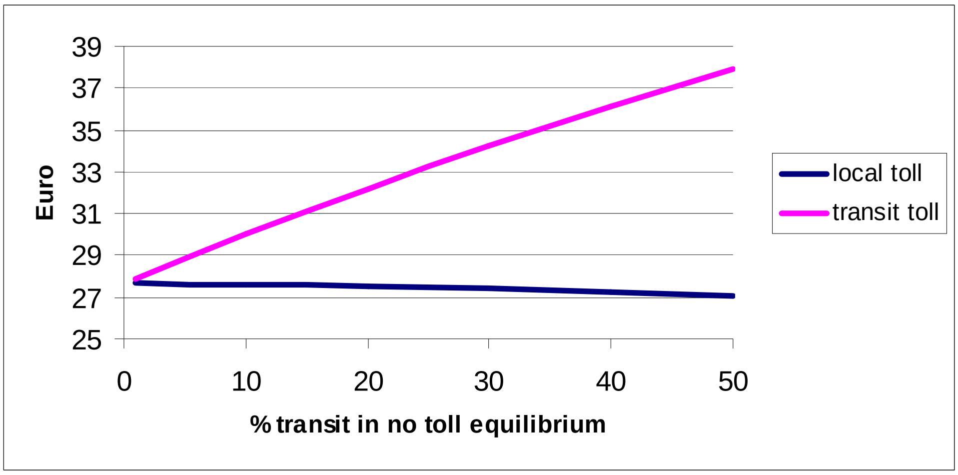
- A uniformity restriction for local and transit tolls does not protect transit from large welfare losses.

4.2 The importance of the share of transit in the no-toll equilibrium

The transit share in the central scenario was 50% in both countries. In this sub-section we briefly illustrate the impact of changing the relative importance of transit. The countries are still assumed to be symmetric.

First consider Figure 1 below. It shows, for the Nash equilibrium tolls with differentiated tolling, the effects of varying the share of transit between 1% and 50%, while keeping the no-toll total traffic volumes at the levels of the central scenario (so this reflects ‘constant congestion’ compared to the central scenario). We see that the transit toll rises dramatically as the share of transit increases, while the local transit toll slightly declines. The latter effect follows from the higher transit toll, which leads to lower traffic levels and, therefore, lower (global) marginal external costs. Finally, note that as the transit share goes to zero, the model converges to marginal social cost pricing for both transport types.

Figure 1 Tolls as a function of no-toll transit share



Next, we check whether the qualitative results concerning the welfare impacts of various pricing constraints depend on the importance of transit. Table 4 presents results from scenarios S1 – S6 for a reference transit share of 10% (instead of 50% in Table 4); Tables 3 and 4 in Appendix 5 contain more detail. Three effects are noteworthy. First, the lower transit share induces a much higher local toll in the Nash equilibrium with zero tolls on transit. The reason is that, for a given increase in tax revenue on local traffic, the increase in congestion due to rising transit is smaller than before. Second, the welfare loss from not coordinating between countries (compare S2 and S5) is even smaller than in the central scenario, as there is less transit and therefore less of a conflict between local and global welfare. Third, not surprisingly, with low transit shares the inability to toll transit traffic is much less detrimental than in the central scenario. In scenario S4, the Nash equilibrium with a local toll only, 62% of the gain from the gain in the Nash equilibrium with differentiation (S2) is obtained. It is still the case that the Nash equilibrium with uniform tolls (S3) does better than welfare maximisation with local tolls only (S6).

Table 4 Key results for the '10% transit share' scenario (50% share of transit traffic)

	S1 No tolls	S2 NE – diff.	S3 NE – unif.	S4 NE - local	S5 Centr. – diff.	S6 Centr. – local
Local toll (Euro/trip)	0	27.6	29.6	12.3	27.7	27.6
Transit toll (Euro/trip)	0	30.0	29.6	0	27.7	0
Local MEC (Euro/trip)	28.0	24.9	24.7	26.6	24.9	24.9
Global MEC (Euro/trip)	31.1	27.6	27.4	29.7	27.7	28.0
Share max. W gain (%)	0	99.9	99.6	62.5	100	89.7
Transit share in total W (%)	10	7.6	7.6	10.0	7.8	10.1

4.3 The effects of asymmetry between countries

4.3.1 Asymmetrical local demand functions

We now consider the effects of differences between countries in local demand functions. More precisely, (i) the transit demand function is assumed to be the same as before; (ii) the sum of local demand over both countries is the same as before; (iii) but, local demand in country A is decreased and that in country B is increased (in the reference case, the no-toll equilibrium). The local demand functions are adapted accordingly (implying both a shift and a change in slope, as the reference elasticity of demand is held constant).

To interpret the economics of the simulations reported here, note that aggregate trip demand for the whole network in the no-toll equilibrium is held at the level of the central scenario, but that only the distribution of local traffic (and, as a consequence, of equilibrium transit demand) between countries is changed. In other words, we look at differences in local demand relative to the available road capacity: for any given level of transit demand, country A has lower congestion than country B. Therefore, the scenario could be interpreted as the case of a densely (B) populated versus a sparsely (A) populated country. Given constant road capacity, more transit is automatically attracted to A. The scenario therefore also reflects differences in the potential of countries to attract transit.

In order to keep the analysis transparent, we limit the discussion to the effects of the described asymmetry for the reference zero toll scenario and for the Nash equilibrium with differentiated tolls. Results are summarised in Table 5 (more detail is in Table 5 of appendix

5). Table 5a first describes the effects of the asymmetry on the reference equilibrium when we decrease, from left to right, local demand in country A; correspondingly, local demand in B rises. Since road capacity does not change, a larger share of overall transit demand, which is constant, is attracted to Country A. By construction, the local marginal congestion cost in Country A decreases, that in Country B increases and, in the reference equilibrium, the generalized cost and the global marginal congestion costs are the same as in the central scenario in both countries.

Table 5b presents the most relevant results. First, asymmetry implies a lower local toll and a higher transit toll in the low-demand Country A, with the opposite directions of change in Country B. Second, its attractiveness for transit implies that global marginal congestion costs in Country A rise (they decrease less compared to the symmetric reference); the opposite holds for B. However, note in both cases that the magnitude of these effects is limited even at very high levels of asymmetry. Third, the effect of the asymmetry on the total transit demand reduction is very small: it is 15.5% in the central scenario and 15% in the most extreme asymmetric scenario. Not surprisingly, as Country A carries more transit flow (in relative and in absolute terms), moving from the reference case to the Nash equilibrium implies a larger reduction in its share in total transit flow. Fourth, the welfare gain from introducing the Nash differentiated tolls in Country A strongly rises when its local willingness to pay for trips becomes smaller; correspondingly, the gains for Country B become smaller. The reduction in total transit welfare after introduction of the differentiated tolls hardly depends on the asymmetry.

Table 5a Asymmetrical local demand functions: the no-toll equilibrium

	Central Symmetric	Asymmetrical scenarios (Increasing asymmetry)	
Share of country A (country B) in trip demand*	25 (25)	15 (35)	ε (50-ε)
Share of transit trips going through country A	50	69.2	100-ε
Local MEC in country A (Euro/trip)	15.6	9.7	ε
Local MEC in country B (Euro/trip)	15.6	21.5	31.2-ε
Global MEC (Euro/trip)	31.1	31.1	31.1

* The transit share is 50% in all scenarios

Table 5b Asymmetrical local demand functions: the Nash equilibrium with differentiated tolls

	Central Symmetric	Asymmetrical scenarios (Increasing asymmetry)	
Local toll in Country A (Country B), Euro/trip	27.1 (27.1)	25.6 (28.5)	23.0 (30.4)
Transit toll in Country A (Country B), Euro/trip	37.9 (37.9)	39.2 (36.4)	40.9 (33.4)
Local MEC in Country A (Country B), Euro/trip	14.0 (14.0)	8.8 (18.9)	ε (27.0)
Global MEC in Country A (Country B), Euro/trip	27.1 (27.1)	25.6 (28.5)	23.0 (30.4)
Change in share of transit trips through country A (%-point)	0	-5.0	-13.2
% welfare change in Country A (Country B)	31.6 (31.6)	67.2 (15.4)	To infinity (2.2)
% welfare change for transit	-28.6	-28.5	-27.7

The economic interpretation of this exercise is clear. It suggests that a country which is in a position to attract a lot of transit traffic, because it has high road capacity and/or little local demand, will highly benefit from a differentiated toll on local and transit traffic. The competitive advantage that follows from having sufficient capacity that is not yet congested by local users enables the country to raise substantial amounts of toll revenue from transit users, so increasing local welfare. The welfare potential of the competing country decreases, but transit users are hardly affected. The example therefore also suggests that countries may have strategic incentives for provision of infrastructure. Endogenising capacity provision seems therefore to be a worthwhile extension of this paper.

4.3.2 Asymmetrical congestion functions

Finally, we test the sensitivity of the results to differences in the congestion functions between countries. The scenario analysed is the following: (i) the congestion function for Country B is the same as in the central scenario; (ii) for Country A, the slope is decreased, simultaneously increasing the intercept in order to retain the volumes and travel times (in both countries) of the central scenario. Consequently, we reduce the 'congestibility' of the road in Country A, but the fixed component of travel time is simultaneously increased.

In economic terms, this scenario can be interpreted as introducing an asymmetry in the relative length and, at given traffic levels, degrees of congestion. The proposed adjustment has the same effect as making the road via Country A longer but less congested (at given traffic levels) compared to the link via country B. Loosely speaking, at given levels of local demand, transit now has the choice between a longer trip with potentially less congestion and a shorter but more congested route. From the viewpoint of transit, given the unchanged parameters for country B, the changes for A imply that the congestibility of the whole network declines.

Table 6a Asymmetrical congestion functions: the no-toll equilibrium

	Central Symmetric	Asymmetrical scenarios (Increasing asymmetry)	
Share of country A (country B) in trip demand*	25 (25)	25 (25)	25 (25)
Share of transit trips going through country A	50	50	50
Local MEC in country A (Euro/trip)	15.6	14.0	ε
Local MEC in country B (Euro/trip)	15.6	15.6	15.6
Global MEC in country A (Euro/trip)	31.1	28.0	ε
Global MEC in country B (Euro/trip)	31.1	31.1	31.1

* The transit share is 50% in all scenarios

Table 6b Asymmetrical congestion functions: the Nash equilibrium with differentiated tolls

	Central Symmetric	Asymmetrical scenarios (Increasing asymmetry)	
Local toll in Country A (Country B), Euro/trip	27.1 (27.1)	24.8 (27.0)	ε (23.7)
Transit toll in Country A (Country B), Euro/trip	37.9 (37.9)	35.9 (37.0)	16.1 (23.6)
Local MEC in Country A (Country B), Euro/trip	14.0 (14.0)	12.6 (14.0)	ε (14.4))
Global MEC in Country A (Country B), Euro/trip	27.1 (27.1)	24.8 (27.0)	ε (23.7)
Change in share of transit trips through country A (%-point)	0	0.87	18.0
% welfare change in Country A (Country B)	31.6 (31.6)	30.2 (30.5)	18.6 (18.6)
% welfare change for transit	-28.6	-27.6	-14.2

Table 6 summarises results (cf. Appendix 5, Table 6 for details). It has the same structure as Table 5 above. In the first asymmetrical scenario, the slope of the congestion function of Country A is gradually reduced by 10% and the intercept is adapted to keep reference volumes and distributions constant (see Table 6a). In the second asymmetrical scenario, the slope of the congestion function of Country A is reduced to epsilon, implying a virtual absence of congestion. The main results are in Table 6b. First, introducing the asymmetry reduces all the optimal tolls, reflecting the decline in congestion at given traffic levels. Second, the effects are largest for the local tolls in the least congested Country A; tolls in B are much less sensitive. Third, the welfare effects of the asymmetry in congestion functions for the Nash equilibrium with toll differentiation are limited (both local and transit welfare), except in the extreme case of zero congestion in A. The local welfare gains from the tolls decrease, which could be expected as the initial inefficiency from congestion becomes smaller with the network capacity increase. Overall, the simulation results suggest that countries with very different demand and congestion conditions will benefit from tolling transit.

5. Summary, conclusions and directions for future research

In this paper we studied optimal and strategic pricing of local and transit traffic on a simple parallel network. The tolling authority on the individual links of the network was assumed to be assigned to different countries. We first theoretically analysed Nash equilibria in this setting for three types of pricing structures: differentiated tolls between local and transit traffic, uniform tolls, and local tolls only. Then a numerical model was used to illustrate the main results and to assess the welfare effects of various pricing constraints and of (the lack of) coordination between countries. The relevance of the share of transit in total transport demand and of asymmetries between countries was numerically illustrated.

The conclusions are easily summarised. First, the welfare effects of tolling transit seem to be large, but the precise type of transit tolling has relatively small effects on efficiency improvements, compared to the no tolling situation. Specifically, differentiation between local and transit tolls as compared to uniform tolls does not yield large welfare differences, although obviously tolls on transit may differ substantially. Allowing differentiated tolls in an uncoordinated setting tends to go at the expense of transit traffic. Second, the welfare effects of coordination between countries are relatively small in comparison with the welfare gains of tolling transit. The outcome when countries behave strategically but do tax transit (e.g., the Nash equilibrium with uniform tolls) yields higher welfare effects than the coordinated welfare optimum for the network as a whole when transit is not tolled. Third, the effect of higher transit shares on the Nash equilibrium with differentiated tolls is to strongly raise the transit toll and to slightly decrease the local toll. As the transit share goes to zero, the model converges to marginal social cost pricing for local traffic. Fourth, the impact of introducing asymmetries between countries is to raise welfare gains for the country with lower local demand (comparing the Nash-equilibrium to the no-toll equilibrium); welfare gains in the other country become less pronounced.

The paper could be extended along several lines. First, we have limited the analysis to cases where at all equilibria both local and transit transport occur in both regions. Although the case of zero local traffic is not very interesting, allowing corner solutions at zero transit does seem a relevant case to consider. Under specific conditions, countries could actually choose to eliminate all transit on their territory. Second, different pricing instruments (road pricing, fuel taxes, vignettes, etc.) could be introduced. This would probably make the theoretical analysis intractable, but it would enrich the numerical results. Third, one could incorporate freight transport and analyse partial taxation of the network (e.g., tolling trucks but not passengers). Fourth, the transition process of introducing tolling instruments sequentially could be explicitly studied. For example, given that one country moves from a system with local tolls only to a system with explicit transit tolling, how does this affect optimal responses by the other country? Alternatively, if a country moves from differentiated tolls towards uniform tolls, what is the optimal response for the other country?

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Appendix 1: Detailed analysis of the case of differentiated tolls

In this appendix we study in more detail the case of differentiated tolls on local and transit transport. We derive the reduced form demand system and discuss its properties, and we derive the optimal toll results presented in the main body of the paper.

The reduced-form demand system

Using (1) and focusing on the case where there is local and transit traffic in both regions, the system consisting of (2), (3) and (4) can be reformulated as

$$P^X(X_A + X_B) = C_A(X_A + Y_A) + \tau_A \qquad \text{(A.1)}$$

$$P^X(X_A + X_B) = C_B(X_B + Y_B) + \tau_B \qquad \text{(A.2)}$$

$$P_A^Y(Y_A) = C_A(X_A + Y_A) + t_A \qquad \text{(A.3)}$$

$$P_B^Y(Y_B) = C_B(X_B + Y_B) + t_B \qquad \text{(A.4)}$$

This system of four equations can easily be solved for the reduced form demand functions as functions of the four tax rates. A particularly instructive way to do this is to first solve (A.3) and (A.4) separately for the demands for local transport as a function of transit demands and local tax rates in a given region:

$$Y_A = z_A(X_A, t_A) \qquad \text{(A.5)}$$

$$Y_B = z_B(X_B, t_B) \qquad \text{(A.6)}$$

Note that application of the implicit function theorem to (A.3) implies:

$$\frac{\partial z_A}{\partial X_A} = \frac{\dfrac{\partial C_A}{\partial V_A}}{\dfrac{\partial P_A^Y}{\partial Y_A} - \dfrac{\partial C_A}{\partial V_A}} < 0 \qquad \text{(A.7)}$$

$$\frac{\partial z_A}{\partial t_A} = \frac{1}{\dfrac{\partial P_A^Y}{\partial Y_A} - \dfrac{\partial C_A}{\partial V_A}} < 0 \qquad \text{(A.8)}$$

where

$$V_A = X_A + Y_A$$

is the total transport volume in A. Using (A.4), an analogous result is derived for B. Interpretation is simple: an exogenous increase in transit in a given region reduces the demand for local transport, as it raises local congestion and hence generalised user cost. Raising the local tax, at a given transit level, reduces local demand for transport.

Substituting (A.5)-(A.6) into (A.1) and (A.2) yields:

$$P^X(X_A + X_B) = C_A\left[X_A + z_A(X_A, t_A)\right] + \tau_A \tag{A.9}$$

$$P^X(X_A + X_B) = C_B\left[X_B + z_B(X_B, t_B)\right] + \tau_B \tag{A.10}$$

The solution of this system yields the reduced-form demand functions for transit, denoted in the main body of the paper as $X_A^r[\tau_A, t_A, \tau_B, t_B]$ and $X_B^r[\tau_A, t_A, \tau_B, t_B]$, respectively. To determine the signs of the various tax effects on transit demands, totally differentiate system (A.9)-(A.10) and write the result in matrix notation:

$$\begin{bmatrix} \frac{\partial P^X}{\partial X} - \frac{\partial C_A}{\partial V_A}(1+\frac{\partial z_A}{\partial X_A}) & \frac{\partial P^X}{\partial X} \\ \frac{\partial P^X}{\partial X} & \frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B}) \end{bmatrix} \begin{bmatrix} dX_A \\ dX_B \end{bmatrix} = \begin{bmatrix} \frac{\partial C_A}{\partial V_A}\frac{\partial z_A}{\partial t_A} dt_A + d\tau_A \\ \frac{\partial C_B}{\partial V_B}\frac{\partial z_B}{\partial t_B} dt_B + d\tau_B \end{bmatrix}$$

Applying Cramers' rule then yields, after simple algebra, the effects of tax changes on demand in A (analogous results hold for B):

$$\frac{dX_A}{dt_A} = \frac{1}{\Delta}\left\{\left(\frac{\partial C_A}{\partial V_A}\frac{\partial z_A}{\partial t_A}\right)\left[\frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})\right]\right\} \tag{A.11}$$

$$\frac{dX_A}{d\tau_A} = \frac{1}{\Delta}\left[\frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})\right] \tag{A.12}$$

$$\frac{dX_A}{dt_B} = -\frac{1}{\Delta}\left(\frac{\partial P^X}{\partial X}\frac{\partial C_B}{\partial V_B}\frac{\partial z_B}{\partial t_B}\right) \tag{A.13}$$

$$\frac{dX_A}{d\tau_B} = -\frac{1}{\Delta}\frac{\partial P^X}{\partial X} \tag{A.14}$$

where

$$\Delta = -\frac{\partial C_A}{\partial V_A}(1+\frac{\partial z_A}{\partial X_A})\left[\frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})\right] - \frac{\partial P^X}{\partial X}\frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})$$

Using (A.7) for k=A,B it follows:

$$(1+\frac{\partial z_k}{\partial X_k}) = \frac{\frac{\partial P_k^Y}{\partial Y_k}}{\frac{\partial P_k^Y}{\partial Y_k} - \frac{\partial C_k}{\partial V_k}} > 0$$

which immediately implies $\Delta > 0$. Note that (A.11)-(A.14) then imply:

$$\frac{dX_A}{d\tau_A} = \frac{\partial X_A^r}{\partial \tau_A} < 0,\ \frac{dX_A}{d\tau_B} = \frac{\partial X_A^r}{\partial \tau_B} > 0,\ \frac{dX_A}{dt_A} = \frac{\partial X_A^r}{\partial t_A} > 0, \frac{dX_A}{dt_B} = \frac{\partial X_A^r}{\partial t_B} < 0$$

Moreover, (A.8), (A.11) and (A.12) imply $\left|\frac{\partial X_A^r}{\partial \tau_A}\right| > \left|\frac{\partial X_A^r}{\partial t_A}\right|$.

Finally, to determine the impact of taxes on local demands, note from (A.5)-(A.6) that

$$\frac{dY_A}{dt_A} = \frac{\partial z_A}{\partial X_A}\frac{dX_A}{dt_A} + \frac{\partial z_A}{\partial t_A}$$
$$\frac{dY_A}{d\tau_A} = \frac{\partial z_A}{\partial X_A}\frac{dX_A}{d\tau_A}$$
$$\frac{dY_A}{dt_B} = \frac{\partial z_A}{\partial X_A}\frac{dX_A}{dt_B}$$
$$\frac{dY_A}{d\tau_B} = \frac{\partial z_A}{\partial X_A}\frac{dX_A}{d\tau_B}$$

so that, using (A.11)-(A.14), it immediately follows:

$$\frac{dY_A}{d\tau_A} = \frac{\partial Y_A^r}{\partial \tau_A} > 0, \frac{dY_A}{d\tau_B} = \frac{\partial Y_A^r}{\partial \tau_B} < 0, \frac{dY_A}{dt_A} = \frac{\partial Y_A^r}{\partial t_A} < 0, \frac{dY_A}{dt_B} = \frac{\partial Y_A^r}{\partial t_B} > 0$$

For the reduced form demand functions for country B, the signs of the different tax effects are determined completely analogously.

Optimal tax rules

Consider problem (8):

$$\underset{t_A,\tau_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + t_A Y_A + \tau_A X_A \,.$$

The first-order condition with respect to t_A is given by:

$$p_A^Y \frac{\partial Y_A^r}{\partial t_A} - g_A^Y \frac{\partial Y_A^r}{\partial t_A} - Y_A \frac{\partial g_A^Y}{\partial t_A} + t_A \frac{\partial Y_A^r}{\partial t_A} + Y_A + \tau_A \frac{\partial X_A^r}{\partial t_A} = 0$$

To simplify this expression, note from (3) that:

$$P_A^Y(Y_A) = g_A^Y = C_A(X_A + Y_A) + t_A$$

which implies by differentiation:

$$\frac{\partial g_A^Y}{\partial t_A} = \frac{\partial C_A}{\partial V_A}\left(\frac{\partial X_A^r}{\partial t_A} + \frac{\partial Y_A^r}{\partial t_A}\right) + 1$$

Using these results in the first-order condition yields:

$$\left(t_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial Y_A^r}{\partial t_A} + \left(\tau_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial X_A^r}{\partial t_A} = 0 \qquad \text{(A.15)}$$

A similar procedure is used to show that the first-order condition with respect to τ_A can be written as:

$$\left(t_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial Y_A^r}{\partial \tau_A} + \left(\tau_A - Y_A \frac{\partial C_A}{\partial V_A}\right)\frac{\partial X_A^r}{\partial \tau_A} + X_A = 0 \qquad \text{(A.16)}$$

To determine the optimal taxes, we write the system in matrix notation and solve by Cramers' rule. We find the following tax rule for local traffic:

$$t_A = \frac{1}{D}\left\{Y_A \frac{\partial C_A}{\partial V_A}[D] + X_A \frac{\partial X_A^r}{\partial t_A}\right\} \qquad \text{(A.17)}$$

where

$$D = \frac{\partial Y_A^r}{\partial t_A}\frac{\partial X_A^r}{\partial \tau_A} - \frac{\partial Y_A^r}{\partial \tau_A}\frac{\partial X_A^r}{\partial t_A}$$

To simplify expression (A.17), first note that, using:

$$\frac{\partial Y_A^r}{\partial t_A} = \frac{\partial z_A}{\partial t_A} + \frac{\partial z_A}{\partial X_A}\frac{\partial X_A^r}{\partial t_A}$$
$$\frac{\partial Y_A^r}{\partial \tau_A} = \frac{\partial z_A}{\partial X_A}\frac{\partial X_A^r}{\partial \tau_A}$$

the term D can be rewritten as:

$$D = \frac{\partial z_A}{\partial t_A}\frac{\partial X_A^r}{\partial \tau_A}$$

Substituting in (A.17) and slightly manipulating the result immediately gives the local tax:

$$t_A = (Y_A + X_A)\frac{\partial C_A}{\partial V_A} = LMEC_A + X_A\frac{\partial C_A}{\partial V_A} \qquad \text{(A.18)}$$

Using similar procedures we find for the transit tax

$$\tau_A = Y_A\frac{\partial C_A}{\partial V_A} - X_A\left[\frac{\frac{\partial Y_A^r}{\partial t_A}}{\frac{\partial z_A}{\partial t_A}\frac{\partial X_A^r}{\partial \tau_A}}\right] \qquad \text{(A.19)}$$

which, using (A.8), yields equation (12) in the text.

Finally, comparison of (A.18) and (A.19) implies that the tax on transit exceeds the tax on local transport. To see this, note that we have:

$$\tau_A - t_A = -X_A\left[\frac{\partial C_A}{\partial V_A} + \frac{\frac{\partial Y_A^r}{\partial t_A}}{\frac{\partial z_A}{\partial t_A}\frac{\partial X_A^r}{\partial \tau_A}}\right]$$

Substituting $\frac{\partial Y_A^r}{\partial t_A} = \frac{\partial z_A}{\partial X_A}\frac{\partial X_A^r}{\partial t_A} + \frac{\partial z_A}{\partial t_A}$, using $\frac{\partial z_A}{\partial X_A} = \frac{\partial C_A}{\partial V_A}\frac{\partial z_A}{\partial t_A}$ (see (A.7)-(A.8)) and rearranging yields

$$\tau_A - t_A = -X_A \left[\frac{1 + \frac{\partial C_A}{\partial V_A} \left[\frac{\partial X_A^r}{\partial \tau_A} + \frac{\partial X_A^r}{\partial t_A} \right]}{\frac{\partial X_A^r}{\partial \tau_A}} \right]$$

Using (A.11)-(A.12) and explicitly substituting for Δ then yields, after some manipulation:

$$\tau_A - t_A = X_A \left[\frac{\frac{\partial P^X}{\partial X} \frac{\partial C_B}{\partial V_B} \left[1 + \frac{\partial z_B}{\partial X_B} \right]}{\frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B} \left[1 + \frac{\partial z_B}{\partial X_B} \right]} \right] > 0$$

Appendix 2: Detailed analysis of the case of uniform tolls

Reduced-form demand system

The procedure to derive the reduced-form demand system is entirely analogous to the differentiated tolling case; the only difference is that we set both the local toll $t_k\ (k = A, B)$ and the transit tolls $\tau_k\ (k = A, B)$ in equations (A.1)-(A.4) equal to the uniform tolls $\theta_k\ (k = A, B)$. Going through exactly the same derivations as in Appendix 1 we easily derive the equivalent of expressions (A.9-A.10):

$$P^X(X_A + X_B) = C_A\left[X_A + z_A(X_A, \theta_A)\right] + \theta_A$$

$$P^X(X_A + X_B) = C_B\left[X_B + z_B(X_B, \theta_B)\right] + \theta_B$$

Differentiating, writing the result in matrix notation and solving by Cramer's rule, we obtain the partial effects of the uniform taxes on demands (the definition of $\Delta > 0$ is the same as in Appendix 1):

$$\frac{dX_A}{d\theta_A} = \frac{1}{\Delta}\left\{ \left(1 + \frac{\partial C_A}{\partial V_A} \frac{\partial z_A}{\partial \theta_A} \right) \left[\frac{\partial P^X}{\partial X} - \frac{\partial C_B}{\partial V_B} (1 + \frac{\partial z_B}{\partial X_B}) \right] \right\} < 0 \qquad \text{(A.20)}$$

$$\frac{dX_A}{d\theta_B} = \frac{-1}{\Delta}\left[\frac{\partial P^X}{\partial X}\left(1+\frac{\partial C_B}{\partial V_B}\frac{\partial z_B}{\partial X_B}\right)\right] > 0 \qquad \text{(A.21)}$$

Moreover, similar procedures as in the case of differentiated taxes immediately yield:

$$\frac{dY_A}{d\theta_A} < 0, \frac{dY_A}{d\theta_B} < 0$$

<u>Optimal tax rules</u>

The first-order condition to the problem

$$\underset{\theta_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + \theta_A(Y_A + X_A),$$

can be written as:

$$P_A^Y \frac{\partial Y_A^r}{\partial \theta_A} - g_A^Y \frac{\partial Y_A^r}{\partial \theta_A} - Y_A \frac{\partial g_A^Y}{\partial \theta_A} + \theta_A(\frac{\partial Y_A^r}{\partial \theta_A} + \frac{\partial Y_A^r}{\partial \theta_A}) + (Y_A^r + X_A^r) = 0$$

To simplify, use:

$$P_A^Y(Y_A) = g_A^Y = C_A(X_A + Y_A) + \theta_A,$$

differentiate with respect to θ_A ,and substitute to obtain:

$$-Y_A\left[\frac{\partial C_A}{\partial V_A}\left(\frac{\partial Y_A^r}{\partial \theta_A} + \frac{\partial X_A^r}{\partial \theta_A}\right)+1\right] + \theta_A(\frac{\partial Y_A^r}{\partial \theta_A} + \frac{\partial Y_A^r}{\partial \theta_A}) + (Y_A^r + X_A^r) = 0$$

Solving for the tax finally yields:

$$\theta_A = Y_A \frac{\partial C_A}{\partial V_A} - \frac{X_A^r}{\frac{\partial Y_A^r}{\partial \theta_A} + \frac{\partial X_A^r}{\partial \theta_A}}$$

Appendix 3: Detailed analysis of the case 'local tolls only'

Reduced-form demand system

The derivatives of the reduced-form demand functions with respect to the local tolls are easily shown to be identical to those for the differentiated tolling case: they are given by equations (A.11) and (A.13). Indeed, the only difference is that the transit toll is set to zero.

Optimal tax rules

The first-order condition to the problem

$$\underset{t_A}{Max} \quad W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + t_A Y_A$$

can be written, using the same simple manipulations as in previous cases, as:

$$t_A \frac{\partial Y_A^r}{\partial t_A} - \left(Y_A \frac{\partial C_A}{\partial V_A} \right) \left(\frac{\partial Y_A^r}{\partial t_A} + \frac{\partial X_A^r}{\partial t_A} \right) = 0$$

Solving for the optimal local toll leads to:

$$t_A = Y_A \frac{\partial C_A}{\partial V_A} \left[1 + \frac{\frac{\partial X_A^r}{\partial t_A}}{\frac{\partial Y_A^r}{\partial t_A}} \right]$$

Importantly, the term between square brackets can be shown to be between zero and one. The implication is economically important. It implies that the optimal tax is positive but smaller than the local marginal external cost.

To show this proposition, note that the bracketed term is obviously smaller than one, since $\frac{\partial Y_A^r}{\partial t_A} < 0, \frac{\partial X_A^r}{\partial t_A} > 0$. To show that is positive it suffices to show that $\frac{\partial Y_A^r}{\partial t_A} + \frac{\partial X_A^r}{\partial t_A} < 0$. To do so, first use (A.5) to find:

$$\frac{\partial Y_A^r}{\partial t_A}+\frac{\partial X_A^r}{\partial t_A}=\frac{\partial z_A}{\partial t_A}+\frac{\partial z_A}{\partial X_A}\frac{\partial X_A^r}{\partial t_A}+\frac{\partial X_A^r}{\partial t_A}=\frac{\partial z_A}{\partial t_A}+(1+\frac{\partial z_A}{\partial X_A})\frac{\partial X_A^r}{\partial t_A}$$

Then substitute (A.11) for $\frac{\partial X_A^r}{\partial t_A}$ to obtain:

$$\frac{\partial Y_A^r}{\partial t_A}+\frac{\partial X_A^r}{\partial t_A}=\frac{\partial z_A}{\partial t_A}+(1+\frac{\partial z_A}{\partial X_A})\left\{\frac{1}{\Delta}\frac{\partial C_A}{\partial V_A}\frac{\partial z_A}{\partial t_A}[M]\right\}=\frac{1}{\Delta}\frac{\partial z_A}{\partial t_A}\left[\Delta+(1+\frac{\partial z_A}{\partial X_A})\frac{\partial C_A}{\partial V_A}[M]\right]$$

where $$M=\frac{\partial P^X}{\partial X}-\frac{\partial C_B}{\partial V_B}\left[1+\frac{\partial z_B}{\partial X_B}\right]<0$$

Noting that we can write Δ as:

$$\Delta=-\frac{\partial C_A}{\partial V_A}(1+\frac{\partial z_A}{\partial X_A})[M]-\frac{\partial P^X}{\partial X}\frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})$$

and substituting we finally have, after simple manipulation, that:

$$\frac{\partial Y_A^r}{\partial t_A}+\frac{\partial X_A^r}{\partial t_A}=-\frac{1}{\Delta}\frac{\partial z_A}{\partial t_A}\left[\frac{\partial P_X}{\partial X}\frac{\partial C_B}{\partial V_B}(1+\frac{\partial z_B}{\partial X_B})\right]<0$$

Appendix 4: Details on the reaction functions and the Nash equilibria

1. The case of differentiated tolls

We consecutively derive the reduced-form demands, the reaction functions, and the Nash equilibrium. To get the reduced-form demands, we follow the procedure outlined in Appendix 1 for the linear demand and cost functions given in the main body of the paper. The demands for local transport conditional on transit and the local tax are given by

$$\begin{aligned}Y_A&=z_0^A+z_1^AX_A+z_2^At_A\\Y_B&=z_0^B+z_1^BX_B+z_2^Bt_B\end{aligned}\qquad\text{(A.23)}$$

where

$$z_0^A = \frac{c_A - \alpha_A}{d_A + \beta_A}, z_1^A = -\frac{\beta_A}{d_A + \beta_A}, z_2^A = -\frac{1}{d_A + \beta_A} \qquad \text{(A.24)}$$

$$z_0^B = \frac{c_B - \alpha_B}{d_B + \beta_B}, z_1^B = -\frac{\beta_B}{d_B + \beta_B}, z_2^B = -\frac{1}{d_B + \beta_B} \qquad \text{(A.25)}$$

Substituting these functions in the Wardrop equilibrium conditions yields, after some manipulations, the reduced-form demands for transit transport. We find:

$$X_A^r = \gamma_0^A + \gamma_1^A \tau_A + \gamma_2^A \tau_B + \gamma_3^A t_A + \gamma_4^A t_B \qquad \text{(A.26)}$$

$$X_B^r = \gamma_0^B + \gamma_1^B \tau_B + \gamma_2^B \tau_A + \gamma_3^B t_B + \gamma_4^B t_A \qquad \text{(A.27)}$$

where the coefficients are given by

$$\gamma_0^A = \frac{b^2(z_0^B - z_0^A) + (a - bz_0^A)T^B}{N} \qquad \gamma_0^B = \frac{b^2(z_0^A - z_0^B) + (a - bz_0^B)T^A}{N}$$

$$\gamma_1^A = -\frac{\left[b + T^B\right]}{N} \qquad \gamma_1^B = -\frac{\left[b + T^A\right]}{N}$$

$$\gamma_2^A = \frac{b}{N} \qquad \gamma_2^B = \frac{b}{N} \qquad \text{(A.28)}$$

$$\gamma_3^A = -\left\{\frac{z_1^A\left[b + T^B\right]}{N}\right\} \qquad \gamma_3^B = -\left\{\frac{z_1^B\left[b + T^A\right]}{N}\right\}$$

$$\gamma_4^A = \frac{bz_1^B}{N} \qquad \gamma_4^B = \frac{bz_1^A}{N}$$

In these expressions $N = bT^A + bT^B + T^A T^B$, and $T^A = \beta_A(1 + z_1^A)$, $T^B = \beta_B(1 + z_1^B)$. Since, using (A.24)-(A.25), the T^i are easily shown to be positive, it immediately follows that N>0. Therefore, we have

$$\gamma_1^A < 0, \gamma_2^A > 0, \gamma_3^A > 0, \gamma_4^A < 0.$$

$$\gamma_1^B < 0, \gamma_2^B > 0, \gamma_3^B > 0, \gamma_4^B < 0.$$

Note that the reduced form demand functions have a straightforward structure. More precisely, observe that the coefficients of the local and the transit taxes are directly related in the following simple manner (i=A,B):

$$\gamma_3^i = z_1^i \gamma_1^i$$
$$\gamma_4^i = z_1^i \gamma_2^i \tag{A.29}$$

Moreover, using (A.24)-(A.25) it immediately follows that $-1 < z_1^i < 0$ so that:

$$|\gamma_3^i| < |\gamma_1^i|$$
$$|\gamma_4^i| < |\gamma_2^i| \tag{A.30}$$

Finally, note that reduced form demands for local traffic are obtained by inserting the demands for transit (equations (A.26)-(A.27)) into system (A.23).

The reaction functions are derived as follows. First, we use the linear demand and cost functions (expressions (14) and (15)) in the optimal tax rules for country A (equations (A.18)-(A.19)) derived in Appendix 1. This yields:

$$t_A = \beta_A (Y_A + X_A) \tag{A.31}$$

$$\tau_A = \beta_A Y_A + \rho_A X_A \tag{A.32}$$

where

$$\rho_A = -\frac{\dfrac{\partial Y_A^r}{\partial t_A}}{\dfrac{\partial z_A}{\partial t_A} \dfrac{\partial X_A^r}{\partial \tau_A}}$$

Now note from (A.23) and (A.26) that:

$$\frac{\partial z_A}{\partial t_A} = z_2^A, \; \frac{\partial Y_A^r}{\partial t_A} = z_2^A + z_1^A \frac{\partial X_A^r}{\partial t_A}, \; \frac{\partial X_A^r}{\partial t_A} = \gamma_3^A, \; \frac{\partial X_A^r}{\partial \tau_A} = \gamma_1^A$$

This implies that:

$$\rho_A = -\left(\frac{z_2^A + z_1^A \gamma_3^A}{z_2^A \gamma_1^A} \right)$$

Substituting in (A.31)-(A.32), using (A.28) and solving for the tax rates in A as sole functions of the two tax rates in B yields, after some algebra,

$$\tau_A = c_A^{\tau} - (\frac{1}{2}\frac{\gamma_2^A}{\gamma_1^A})\tau_B - (\frac{1}{2}\frac{\gamma_4^A}{\gamma_1^A})t_B$$

$$t_A = c_A^t + (\frac{1}{2}\frac{\gamma_2^A}{\gamma_1^A}K^A)\tau_B + (\frac{1}{2}\frac{\gamma_4^A}{\gamma_1^A}K^A)t_B \tag{A.33}$$

where all coefficients have been defined before, except

$$c_A^{\tau} = \frac{1}{2}\left(\beta_A z_0^A - \frac{\gamma_0^A}{\gamma_1^A}\right)$$

$$c_A^t = \left[\beta_A z_0^A + \frac{1}{2}T^A\left(\beta_A z_0^A \gamma_1^A + \gamma_0^A\right)\right]\frac{K^A}{T^A\gamma_1^A}$$

$$K^A = \frac{T^A\gamma_1^A}{1 - z_1^A(1 + T^A\gamma_1^A)}$$

Moreover, for purposes of the interpretation it is useful to note that $-1 < K^A < 0$. This is easily seen to be the case as follows. First,

$$T^A\gamma_1^A = -\frac{T^A(b+T^B)}{N} = -\frac{T^A(b+T^B)}{bT^A + bT^B + T^AT^B}$$

which implies $-1 < T^A\gamma_1^A < 0$. This in turn implies $-1 < K^A < 0$.

Importantly, since the tax competition problem considered in this section is a game with four tax rates, it is not obvious to prove the existence and uniqueness of Nash equilibrium in this general setting. Fortunately, the linear structure of the problem allows us to reduce the four-dimension game into a policy game in two dimensions; moreover, existence and uniqueness then immediately follow. To see this, consider the structure of the reaction functions (A.33) and note that the local and transit tax rates of each country can be written as a function of the same linear combination of the tax rates of the other country. Specifically, define:

$$\pi_A = \tau_A + z_B^1 t_A$$

$$\pi_B = \tau_B + z_A^1 t_B$$

Substituting this result in (A.33) we obtain:

$$\tau_A = c_A^{\tau} - r^A\pi_B$$

$$t_A = c_A^t - r^AK^A\pi_B$$

where $r^A = \frac{1}{2}\frac{\gamma_2^A}{\gamma_1^A}$. Similar expressions result for region B. We can therefore reformulate (A.33) and its equivalent for B as follows:

$$\pi_A = s^A + p^A \pi_B$$
$$\pi_B = s^B + p^B \pi_A$$

where

$$s^A = c_A^\tau + z_1^B c_A^t$$
$$s^B = c_B^\tau + z_1^A c_B^t$$
$$p^A = -r^A (1 + z_1^B K^A)$$
$$p^B = -r^B (1 + z_1^A K^B)$$

Realising that $-1 < K^i < 0$, simple algebra immediately shows that the reaction functions have a positive intercept, are upward sloping, and that they have a slope less than one. Finally, note that solving the reaction functions for the original four tax rates yields the Nash equilibrium in function of the various coefficients that describe cost and demand responses. The solution is however not transparent and does not yield extra insights.

2. The case of uniform tolls

We follow the same steps and use the same definitions as in the previous case. The reduced-form demands for local transport conditional on transit and the local tax are given by

$$Y_A = z_0^A + z_1^A X_A + z_2^A \theta_A$$
$$Y_B = z_0^B + z_1^B X_B + z_2^B \theta_B \qquad \text{(A.34)}$$

The reduced-form demand functions for transit are now the following:

$$X_A^r = \gamma_0^A + (\gamma_1^A + \gamma_3^A)\theta_A + (\gamma_2^A + \gamma_4^A)\theta_B \qquad \text{(A.35)}$$

$$X_B^r = \gamma_0^B + (\gamma_1^B + \gamma_3^B)\theta_B + (\gamma_2^B + \gamma_4^B)\theta_A \qquad \text{(A.36)}$$

where the coefficients are defined as above.

To obtain the reaction function for region A, use

$$\frac{\partial Y_A^r}{\partial \theta_A} = z_2^A + z_1^A(\gamma_1^A + \gamma_3^A) < 0$$

$$\frac{\partial X_A^r}{\partial \theta_A} = \gamma_1^A + \gamma_3^A < 0$$

in the optimal tax rule derived in Appendix 2:

$$\theta_A = Y_A \frac{\partial C_A}{\partial V_A} - \frac{X_A^r}{\frac{\partial Y_A^r}{\partial \theta_A} + \frac{\partial X_A^r}{\partial \theta_A}}$$

Solving explicitly for the optimal tax, we find the reaction function:

$$\theta_A = \frac{c_2^{tuA}}{c_1^{tuA}} + \frac{c_3^{tuA}}{c_1^{tuA}} \theta_B \qquad \text{(A.37)}$$

where

$$c_1^{tuA} = 1 - z_1^A - (\beta_A z_1^A + \eta_A)(\gamma_1^A + \gamma_3^A)$$

$$c_2^{tuA} = (\beta_A z_1^A + \eta_A)\gamma_0^A + \beta_A z_0^A$$

$$c_3^{tuA} = (\beta_A z_1^A + \eta_A)(\gamma_2^A + \gamma_4^A)$$

and

$$\eta_A = -\frac{1}{(1 + z_1^A)(\gamma_1^A + \gamma_3^A) + z_2^A} > 0$$

Straightforward algebra shows that the reaction functions are upward sloping. To do so, note that it suffices to show that ($\beta_A z_1^A + \eta_A$)>0. This is shown as follows. First, use the definition of the γ_i^A (see (A.28)) in the definition of η_A to obtain:

$$\eta_A = \frac{N}{(1 + z_1^A)^2(b + T^B) - N z_2^A}$$

This yields:

$$\beta_A z_1^A + \eta_A = \frac{\beta_A z_1^A (1 + z_1^A)^2 (b + T^B) - \beta_A z_1^A z_2^A N + N}{(1 + z_1^A)^2 (b + T^B) - N z_2^A})$$

The denominator is positive. The numerator can be written, using $\beta_A(1+z_1^A)=T^A, \beta_A z_2^A = z_1^A$, as:

$$T^A(b+T^B)z_1^A(1+z_1^A)+N\left[1-(z_1^A)^2\right]$$

which is positive, because $-1<z_1^A<0$.

Finally, note that a Nash equilibrium indeed exists. This requires the condition:

$$\frac{c_3^{tuA}}{c_1^{tuA}}\frac{c_3^{tuB}}{c_1^{tuB}}<1$$

Substituting the definition of the coefficients and rearranging it follows that this condition holds.

<u>3. Local tolls only</u>

Again we follow the same steps and use the same definitions as in the section for the differentiated tolls. The demands for local transport conditional on transit and the local tax are given by

$$\begin{aligned} Y_A &= z_0^A + z_1^A X_A + z_2^A t_A \\ Y_B &= z_0^B + z_1^B X_B + z_2^B t_B \end{aligned} \qquad \text{(A.38)}$$

Reduced-form demands for transit are:

$$X_A^r = \gamma_0^A + \gamma_3^A t_A + \gamma_4^A t_B \qquad \text{(A.39)}$$

$$X_B^r = \gamma_0^B + \gamma_3^B t_B + \gamma_4^B t_A \qquad \text{(A.40)}$$

To get the reaction function for country A, use the above specifications in the optimal tax rule

$$t_A = Y_A \frac{\partial C_A}{\partial V_A}(1+\frac{\frac{\partial X_A^r}{\partial t_A}}{\frac{\partial Y_A^r}{\partial t_A}})$$

to find:

$$t_A = \beta_A Y_A \delta_A \quad (A.41)$$

where $$\delta_A = 1 + \frac{\gamma_3^A}{z_2^A + z_1^A \gamma_3^A} = \frac{z_2^A + (1+z_1^A)\gamma_3^A}{z_2^A + z_1^A \gamma_3^A}$$

Note that $\delta_A > 0$. The denominator is negative, since $z_1^A < 0, z_2^A < 0, \gamma_3^A > 0$. The nominator is easily shown to be negative as well. We have

$$z_2^A + (1+z_1^A)\gamma_3^A = z_2^A + (1+z_1^A)\left[-\frac{z_1^A(b+T^B)}{N}\right] = \frac{1}{N}\left\{Nz_2^A - (1+z_1^A)z_1^A(b+T^B)\right\}$$

Noting that $\beta_A z_2^A = z_1^A$ and $\beta_A(1+z_1^A) = T^A$, and using $N = bT^A + bT^B + T^A T^B$ yields:

$$z_2^A + (1+z_1^A)\gamma_3^A = \frac{z_1^A b T^B}{\beta_A N} < 0$$

It follows that $\delta_A > 0$.

Finally, substituting (A.38) in (A.41) and working out the result leads to the reaction function:

$$t_A = \frac{c_2^{tlA}}{c_1^{tlA}} + \frac{c_3^{tlA}}{c_1^{tlA}} t_B \quad (A.42)$$

where the coefficients are $$c_1^{tlA} = 1 - \beta_A \delta_A (z_2^A + z_1^A \gamma_3^A)$$

$$c_2^{tlA} = \beta_A \delta_A (z_0^A + z_1^A \gamma_0^A)$$

$$c_3^{tlA} = \beta_A \delta_A z_1^A \gamma_4^A$$

Using the definition of δ_A is immediately follows that $c_1^{tlA} > 0, c_3^{tlA} > 0$ so that the slope of the reaction function is positive. Moreover, assuming all types of transport exist in the equilibrium, the existence of a Nash equilibrium can be shown. Substitution of the coefficients shows, after simple manipulation, that $\frac{c_3^{tlA}}{c_1^{tlA}} \frac{c_3^{tlB}}{c_1^{tlB}} < 1$.

Appendix 5: Detailed Tables for the numerical illustration

Table 1 Results from symmetric model – Levels, index (S5=100)

Note: these scenarios produce symmetric outcomes, so the distinction between countries A and B is suppressed; variables not defined on the country level are shown in italics

			S1		S2		S3		S4		S5		S6	
			No tolls		NE - differentiation		NE - uniform		NE - local toll only		Centralised - diff.		Centralised - loc. only	
	Variable	Unit	Level	Index	Level	Index	Level	Index	Level	Index	Level	Index	Level	Index
1	Local demand	Trips	1,300	112.5	1,163	100.6	1,108	95.9	1,262	109.2	1,156	100	1,146	99.2
2	*Transit demand*	*Trips*	*2,600*	*112.5*	*2,197*	*95.0*	*2,216*	*95.9*	*2,605*	*112.7*	*2,311*	*100*	*2,620*	*113.4*
3	Trip volume, country level	Trips	2,600	112.5	2,261	97.8	2,216	95.9	2,564	110.9	2,311	100	2,456	106.3
4	Transit volume, country level	Trips	1,300	112.5	1,098	95.0	1,108	95.9	1,302	112.7	1,156	100	1,310	113.4
5	Generalised price, local	Euro/trip	65.4	73.0	88.5	98.7	97.7	109.0	71.8	80.1	89.7	100.0	91.2	101.8
6	*Generalised price, transit*	*Euro/trip*	*65.4*	*73.0*	*99.3*	*110.7*	*97.7*	*109.0*	*65.0*	*72.5*	*89.7*	*100.0*	*63.7*	*71.1*
7	Time cost	Euro/trip	32.7	111.8	28.7	97.9	28.1	96.1	32.3	110.3	29.3	100.0	31.0	105.9
8	**Local toll**	**Euro/trip**	**0.0**	**0.0**	**27.1**	**97.8**	**36.8**	**133.2**	**6.8**	**24.7**	**27.7**	**100.0**	**27.5**	**99.4**
9	**Transit toll**	**Euro/trip**	**0.0**	**0.0**	**37.9**	**137.0**	**36.8**	**133.2**	**0.0**	**0.0**	**27.7**	**100.0**	**0.0**	**0.0**
10	Local MEC	Euro/trip	15.6	112.5	13.9	100.6	13.3	95.9	15.1	109.2	13.8	100.0	13.7	99.2
11	Global MEC	Euro/trip	31.1	112.5	27.1	97.8	26.5	95.9	30.7	110.9	27.7	100.0	29.4	106.3
12	Local CS	Euro	141,748	126.5	113,422	101.2	102,948	91.9	133,558	119.2	112,029	100	110,214	98.4
13	Tax revenue, country level	Euro	0	0.0	73,069	114.3	81,596	127.6	8,606	13.5	63,926	100	31,521	49.3
14=12+13	Welfare, country level	Euro	141,748	80.6	186,492	106.0	184,544	104.9	142,164	80.8	175,955	100	141,735	80.6
15	*Transit welfare (CS)*	*Euro*	*283,495*	*126.5*	*202,364*	*90.3*	*205,894*	*91.9*	*284,603*	*127.0*	*224,057*	*100*	*287,975*	*128.5*
*16=2*14+15*	*Overall welfare*	*Euro*	*566,991*	*98.4*	*575,348*	*99.9*	*574,982*	*99.8*	*568,931*	*98.8*	*575,968*	*100*	*571,445*	*99.2*

Table 2 Distribution of welfare and total welfare gain (%)

	S1	S2	S3	S4	S5	S6
Share country A	25.00	32.41	32.10	24.99	30.55	24.80
Share country B	25.00	32.41	32.10	24.99	30.55	24.80
Share transit	50.00	35.17	35.80	50.02	38.90	50.39
Total (% change compared to S1)	100 (**0.00**)	100 (**1.47**)	100 (**1.41**)	100 (**0.34**)	100 (**1.58**)	100 (**0.78**)

Table 3 Results from symmetric model – Levels, index (S5=100); low transit share in S1 (10%)
Note: these scenarios produce symmetric outcomes, so the distinction between countries A and B is suppressed; variables not defined on the country level are shown in italics

			S1		S2		S3		S4		S5		S6	
			No tolls		NE - differentiation		NE - uniform		NE - local toll only		Centralised - diff.		Centralised - loc. only	
	Variable	Unit	Level	Index	Level	Index	Level	Index	Level	Index	Level	Index	Level	Index
1	Local demand	Trips	2,340	112.5	2,081	100.0	2,062	99.1	2,222	106.8	2,080	100	2,077	99.8
2	*Transit demand*	*Trips*	*520*	*112.5*	*457*	*98.8*	*458*	*99.1*	*523*	*113.2*	*462*	*100*	*527*	*114.1*
3	Trip volume, country level	Trips	2,600	112.5	2,309	99.9	2,291	99.1	2,484	107.5	2,311	100	2,340	101.3
4	Transit volume, country level	Trips	260	112.5	228	98.8	229	99.1	262	113.2	231	100	264	114.1
5	Generalised price, local	Euro/trip	65.4	73.0	89.6	99.9	91.3	101.8	76.4	85.2	89.7	100.0	90.0	100.3
6	*Generalised price, transit*	*Euro/trip*	*65.4*	*73.0*	*92.0*	*102.6*	*91.3*	*101.8*	*64.1*	*71.5*	*89.7*	*100.0*	*62.3*	*69.5*
7	Time cost	Euro/trip	32.7	111.8	29.2	99.9	29.0	99.2	31.3	107.1	29.3	100.0	29.6	101.2
8	**Local toll**	**Euro/trip**	**0.0**	**0.0**	**27.6**	**99.9**	**29.6**	**106.8**	**12.3**	**44.6**	**27.7**	**100.0**	**27.6**	**99.9**
9	**Transit toll**	**Euro/trip**	**0.0**	**0.0**	**30.0**	**108.4**	**29.6**	**106.8**	**0.0**	**0.0**	**27.7**	**100.0**	**0.0**	**0.0**
10	Local MEC	Euro/trip	28.0	112.5	24.9	100.0	24.7	99.1	26.6	106.8	24.9	100.0	24.9	99.8
11	Global MEC	Euro/trip	31.1	112.5	27.6	99.9	27.4	99.1	29.7	107.5	27.7	100.0	28.0	101.3
12	Local CS	Euro	255,146	126.5	201,761	100.1	198,221	98.3	230,180	114.1	201,652	100	201,006	99.7
13	Tax revenue, country level	Euro	0	0.0	64,345	100.7	67,718	105.9	27,403	42.9	63,927	100	57,361	89.7
14=12+13	Welfare, country level	Euro	255,146	96.1	266,106	100.2	265,939	100.1	257,582	97.0	265,579	100	258,367	97.3
15	*Transit welfare (CS)*	*Euro*	*56,705*	*126.5*	*43,756*	*97.6*	*44,055*	*98.3*	*57,428*	*128.1*	*44,817*	*100*	*58,330*	*130.2*
*16=2*14+15*	*Overall welfare*	*Euro*	*566,997*	*98.4*	*575,968*	*100.0*	*575,933*	*100.0*	*572,592*	*99.4*	*575,975*	*100*	*575,064*	*99.8*

Table 4 Distribution of welfare and total welfare gain (%); low transit share in S1 (10%)

	S1	S2	S3	S4	S5	S6
Share country A	45	46.20	46.18	44.98	46.11	44.93
Share country B	45	46.20	46.18	44.98	46.11	44.93
Share transit	10	7.60	7.65	10.03	7.78	10.14
Total (% change compared to S1)	100 (0.00)	100 (1.582)	100 (1.576)	100 (0.99)	100 (1.583)	100 (1.42)

Table 5 Asymmetrical local demand functions

	A: symmetry (central scenario)	B: asymmetric	C: asymmetric	D: asymmetric	E: asymmetric
Characteristics of reference situation					
Reference distribution of demand, % (aggregate demand and transit demand are constant across scenarios)					
Country A	25	21	15	8	ε
Country B	25	29	35	42	50-ε
Transit	50	50	50	50	50
Reference distribution of transit over countries					
Share Country A	50	57.7	69.2	84.6	100-ε
Share Country B	50	42.3	30.8	15.4	ε
Reference marginal congestion cost, Euro/trip, index					
Local MECC A	15.6 (100)	85	62	31	ε
Local MECC B	15.6 (100)	115	138	169	200-ε
Global MECC A	31.1 (100)	100	100	100	100
Global MECC B	31.1 (100)	100	100	100	100
Comparisons of reference situation and Nash equilibrium					
Percentage change of trip demand					
Local demand A	-10.5	-10.0	-9.2	-8.0	-6.8
Local demand B	-10.5	-11.1	-11.8	-12.7	-13.6
Transit demand	-15.5	-15.5	-15.4	-15.3	-15.0
Change in distribution of transit (%-point change in share of Country A = - value for Country B)					
Change share Country A	0	-2.0	-5.0	-9.1	-13.2
Optimal toll, Euro/trip, index					
Local toll A	27.1 (100)	97.9	94.5	89.9	84.9
Local toll B	27.1 (100)	102.1	105.0	108.8	112.2
Transit toll A	37.9 (100)	101.4	103.4	105.8	107.8
Transit toll B	37.9 (100)	98.5	96.0	92.3	88.2
Change in marginal congestion costs, %					
Local MECC A	-10.5	-10.0	-9.2	-8.0	-6.8
Local MECC B	-10.5	-11.1	-11.8	-12.7	-13.6
Global MECC A	-13.0	-14.9	-17.8	-21.8	-26.2
Global MECC B	-13.0	-11.2	-8.7	-5.4	-2.4
Welfare change, %					
Country A	31.6	42.0	67.2	157.4	To infinity
Country B	31.6	23.9	15.4	7.6	2.2
Transit	-28.6	-28.6	-28.5	-28.2	-27.7

Table 6 Asymmetrical congestion functions

	A: symmetry (central scenario)	B: asymmetric	C: asymmetric	D: asymmetric	E: asymmetric
Characteristics of reference situation					
Reference distribution of demand, % (aggregate demand and transit demand are constant across scenarios)					
Country A	25	25	25	25	25
Country B	25	25	25	25	25
Transit	50	50	50	50	50
Reference distribution of transit over countries					
Share Country A	50	50	50	50	50
Share Country B	50	50	50	50	50
Reference marginal congestion cost, Euro/trip, index					
Local MECC A	15.6 (100)	95	90	85	ε
Local MECC B	15.6 (100)	100	100	100	100
Global MECC A	31.1 (100)	95	90	85	ε
Global MECC B	31.1 (100)	100	100	100	100
Comparisons of reference situation and Nash equilibrium					
Percentage change of trip demand					
Local demand A	-10.5	-10.2	-9.8	-9.5	–ε
Local demand B	-10.5	-10.5	-10.4	-10.4	-7.4
Transit demand	-15.5	-15.2	-14.9	-14.6	-7.4
Change in distribution of transit (%-point change in share of Country A = - value for Country B)					
Change share Country A	0	0.42	0.87	1.34	18.0
Optimal toll, Euro/trip, index					
Local toll A	27.1 (100)	95.7	91.4	87.1	ε
Local toll B	27.1 (100)	99.8	99.5	99.3	87.3
Transit toll A	37.9 (100)	97.3	94.6	91.8	42.6
Transit toll B	37.9 (100)	98.5	97.6	95.4	62.4
Change in marginal congestion costs, %					
Local MECC A	-10.5	-10.2	-9.8	-9.5	0
Local MECC B	-10.5	-10.5	-10.4	-10.4	-7.4
Global MECC A	-13.0	-12.3	-11.6	-10.9	13.1
Global MECC B	-13.0	-13.2	-13.4	-13.6	-24.1
Welfare change, %					
Country A	31.6	30.1	30.2	29.5	18.6
Country B	31.6	31.0	30.5	30.0	18.6
Transit	-28.6	-28.1	-27.6	-27.1	-14.2