The Interaction between Tolls and Capacity Investment in Serial and Parallel Transport Networks

BRUNO DE BORGER *

Department of Economics, University of Antwerp

FAY DUNKERLEY

Department of Economics, Catholic University Leuven

STEF PROOST

Department of Economics, Catholic University Leuven

Abstract

The purpose of this paper is to compare price and capacity competition in simple serial and parallel transport networks, where individual links are operated by different authorities. We find more tax exporting in serial transport corridors than on parallel road networks. The inability to toll transit has quite dramatic negative welfare effects on parallel networks; in serial transport corridors, it may actually be undesirable to allow the tolling of transit at all. Finally, if the links are exclusively used by transit transport, toll and capacity decisions are independent in serial networks. When regions compete for transit in a parallel setting, higher regional capacity implies lower Nash equilibrium tolls.

1 Introduction

Congestion is a serious problem in many countries worldwide. Apart from a variety of other measures, economists have long advocated the use of pricing policies to tackle this problem. Moreover, it has been recognized that in the long-run, pricing can be accompanied by investment strategies to alleviate congestion. However, implementing pricing and investment policies on realistic transport networks leads to a number of potential complications. Firstly, since different links (highways, roads, railroads ...) of a network may be under the jurisdiction of different governments and most links are used

* Contact Author. Department of Economics, University of Antwerp, Prinsstraat 13, B-2000 Antwerp, Belgium. E-mail: bruno.deborger@ua.ac.be The first author is grateful to the University of Antwerp for support through its TOP-program; the second and third author benefited from financial support of the FUNDING consortium (6^{th} Framework research Program of the EC (6.2)) on the Funding of the Trans European Networks (www.econ.kuleuven.be/funding). This paper developed out of preliminary work presented at the Third Conference on Railroad Industry Structure, Competition and Investment, Stockholm, October 2005. We are grateful to Guido Friebel and Marcus Ksoll for useful discussions on the issue. Finally, the final version of the paper benefited from the detailed comments of an anonymous referee and the editors of this issue.

both by local transport and by through traffic (transit), the fear exists that competition for transit toll revenues may induce governments or operators to exploit transit transport by imposing high tolls. Governments may also invest strategically to capture transit toll revenues. Finally, when tolling transit is for some reason not feasible, regions may be reluctant to invest in capacity because the benefits accrue to a significant extent to foreigners. In sum, the possibility of strategic behavior by governments and the interaction of local and transit transport raises a number of questions about toll and capacity choices on transport networks: (i) How does investment in infrastructure capacity affect the pricing behavior of governments; (ii) What are the welfare effects of toll and capacity competition for transit; (iii) To what extent do the outcomes of this competition between governments depend on the structure of the transport network.

The purpose of this paper is to study the interaction between pricing and capacity decisions on simple networks, where individual links of the network are operated by different governments. We do this by bringing together and extending the recent literature on the topic. As real-world networks are highly complex, we focus on two stylized network structures in this paper. The first one is a parallel network structure in which long distance transit traffic has a choice between different jurisdictions' 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. Another example is the transalpine crossing between Germany and Italy, where the main links pass either through Austria or through Switzerland. In both examples, transit has a choice of routes and it interacts with local traffic in each country.[1]

The second network structure we consider is a serial transport corridor, which provides a more realistic representation of many road and rail systems. Both the Trans European Networks (basically a border-crossing rail and highway system) in Europe and the interstate highway system in the US fit this setting of serial transport corridors. Moreover, a serial setting applies to inter-modal freight trips where the transfer facility (ports, airports, freight terminal) and the upstream or downstream infrastructure are controlled by different governments. The possibility of strategic behavior in the case of a serial corridor has been noted several times before. In the case of railroads, for example, EU Directive 2001/14 has explicitly argued that coordination between countries is needed in order to avoid the negative effects of the lack of harmonization of different charging systems used by member states. Moreover, Nash (2005) finds some evidence of tax exporting behavior in an analysis of European infrastructure charges.

The issue of optimal pricing and investment decisions on simple transport networks has been studied before. Various studies have considered parallel network structures. For example, different aspects of pricing of congestible parallel roads have been studied by Braid (1986), Verhoef *et al* (1996), De Palma and Lindsey (2000), McDonald and Liu (1999), Small and Yan (2001), and Van Dender (2005). As far as we know, the only study to analyze the problem within the context of toll competition between governments is De Borger, Proost and Van Dender (2005); they do so for fixed capacity, however. Both De Palma and Leruth (1989) and De Borger and Van Dender (2006) study two-stage games in

[1] Note that, with minor adjustments, the choice between two modes that connect a given origin and destination fits within this framework as well. For example, freight connections between ports such as Antwerp or Rotterdam and the Ruhr in Germany have a choice between road, rail or inland waterways. Some transport between Finland and Germany has the choice between shipping (through Kiel) and road modes (via Sweden and Denmark).

capacities and prices for congested facilities but they do not consider the interaction between local and transit traffic and they do not look at issues of tax and capacity competition. Several studies also address strategic behavior in serial transport corridors. One study looks specifically at tax exporting in such a setting but ignores capacity decisions (Levinson (2001)). More recently, De Borger, Dunkerley and Proost (2007) do consider pricing and capacity investment in a two-stage game for a serial network, and illustrate the welfare effects for various sets of tolling instruments. Lastly, Bassanini and Pouyet (2005) study the non-coorperative choice of financing system (that is, does the system allow subsidies to be paid out of general tax revenues) by two national infrastructure managers who maximize welfare in their country while covering network costs. Agrell and Pouyet (2006) extend this work, focusing on countries' incentives to improve investment efficiency.

In this paper, we extend and integrate earlier findings on tax and capacity games between welfare maximizing governments in both serial and parallel networks. Although some of the results of the current paper have been reported separately in the studies referred to above, our focus here is on the differences in the nature and extent of toll and capacity competition between regions, depending on the structure of the network. This yields valuable new insights, as will become clear below. Throughout the paper, we assume that countries maximize a welfare function consisting of local consumer surplus and tax revenues from local and transit traffic, and we study strategic tolling by individual countries under various tolling schemes.

We obtain a number of interesting results. Firstly, if the network is exclusively used by transit transport, we show that toll and capacity decisions are independent in serial networks. In a parallel setting, however, it is shown that extra investment in capacity in a given region leads to lower Nash equilibrium tolls in both regions. The former result does not generalize to a setting with both local and transit demand; the latter does. Secondly, the nature and extent of competition in capacity and tolls differs strongly between network types. For example, in absolute values reaction functions for transit tolls are much more responsive to tolls abroad on serial networks than on parallel ones. The policy implication of this finding is that, ceteris paribus, one expects much more tax exporting behavior hence, higher toll levels in serial transport corridors than on competing parallel road networks. Thirdly, the inability to toll transit has quite dramatic negative welfare effects on parallel networks, partly because it strongly reduces the incentives to invest. On the contrary, in serial transport corridors it may actually be undesirable to toll transit. Again, this has a clear policy implication. It implies that it may not be wise for the EU to allow individual countries to independently decide on toll levels on transit traffic that passes through their jurisdiction.

2 Model description

We distinguish parallel and serial network structures as very simple descriptions of real-world toll and capacity competition problems. The two network structures are shown in Figure 1.

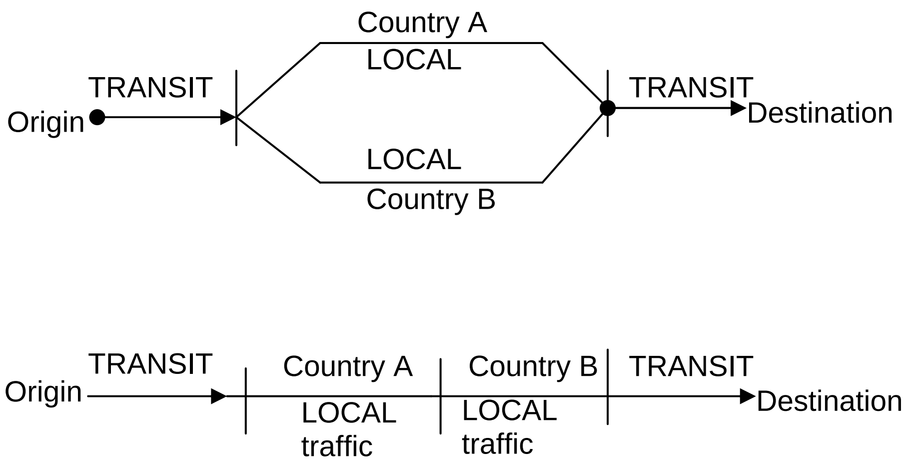

Figure 1: Parallel (upper part) versus serial (lower part) competition

We assume each link carries local traffic and transit traffic. Local traffic uses only the local link. Transit traffic chooses one of the links (parallel case) or passes through the two links (serial case). Note that in both cases, origins and destinations are assumed to lie outside the network. We further 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 capacity of each link can be augmented through investments; however, once capacity is chosen for a given link it is potentially congestible.

Demand for local transport in regions A and B is represented by the strictly downward sloping and twice differentiable 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. As is common in the transport literature, the prices $P_i^j(.)$ are generalized prices including resource costs, time costs and toll payments. Similarly, overall demand for transit traffic is described by the strictly downward sloping inverse demand function $P^X(X)$, where X is the transit traffic flow. Importantly, the treatment of transit differs for parallel and serial settings. We have the following definitions:

Parallel links $X = X_A + X_B$
Serial links $X = X_A = X_B$

In the case of parallel links, total demand for transit is "distributed" over the two alternatives; with serial links, all transit passes through both regions A and B.

We now turn to the cost side. Although other tolling regimes will be considered (see below), here we formulate cost functions for the case of differentiated tolls between local transport and transit traffic. In that case, the generalized user cost functions for local use of links are given by:

$$g_i^Y = C_i(V_i R_i) + t_i \,, \; i = A, B$$

The $C_i(.)$ are the time plus resource costs on link *i*, and R_i is the inverse of capacity. The user cost function is twice differentiable and strictly increasing in V_iR_i, the total traffic volume relative to capacity. Making time costs a function of volume-capacity ratio is a common practice in transport economics (see, for example, Verhoef *et al* (1996)). The t_i are the tolls on local transport. Similarly, the generalized user cost for transit through region $i\left(i = A, B\right)$, denoted as g_i^X, equals the sum of the time and resource costs of travel plus the transit tolls, denoted τ_i:

$$g_i^X = C_i(V_iR_i) + \tau_i \, , i = A, B$$

The transport user equilibrium is defined by equating generalized prices and generalized costs. In the parallel case, it is assumed that from the viewpoint of transit, the two routes are perfect substitutes; moreover, we focus on internal solutions throughout so that we exclude the case where one link is not used at all. Under those conditions the transport user equilibria for the serial and parallel networks can be summarized as follows:

Serial network

$$P_i^Y(Y_i) = g_i^Y \, , i = A, B \qquad (1)$$
$$P^X(X) = g_A^X + g_B^X$$

Parallel network

$$P_i^Y(Y_i) = g_i^Y \, , i = A, B \qquad (2)$$
$$P^X(X) = g_A^X = g_B^X$$

The equilibrium conditions (1) and (2) can be solved for the demands for local and transit traffic as a function of taxes and capacities in both countries. In the case of a serial network structure, solving (1) and using the definitions of the generalized user costs given before, yields the demand functions[2]:

$$Y_A^r(t_A, t_B, \tau_A + \tau_B, R_A, R_B), Y_B^r(t_A, t_B, \tau_A + \tau_B, R_A, R_B)$$
$$X^r(t_A, t_B, \tau_A + \tau_B, R_A, R_B)$$

Similarly, solving (2) implies demand functions:

$$Y_A^r(t_A, t_B, \tau_A, \tau_B, R_A, R_B), Y_B^r(t_A, t_B, \tau_A, \tau_B, R_A, R_B)$$
$$X_A^r(t_A, t_B, \tau_A, \tau_B, R_A, R_B), X_B^r(t_A, t_B, \tau_A, \tau_B, R_A, R_B)$$

[2] These are "reduced" demand functions indicated with a superscript r where the effects of government control parameters (tolls and capacity) on the congestion levels via transit and local demand are integrated.

Note the difference. The serial structure implies demands that depend on local tolls and on the total toll paid by transit. The parallel structure has demands that depend on local tolls and on the individual tolls for transit in A and B.

The analysis of tax and capacity competition is studied for several tax regimes. To be precise, we distinguish between: (i) Different tolls on local and transit traffic; this is the case explained above, where we used τ_i and t_i for the toll on transit and local demand in region i, respectively $\left(i = A, B\right)$; (ii) Uniform tolls on local and transit transport. Uniform tolls are denoted $\theta_i = \tau_i = t_i$; (iii) The case where transit remains un-tolled.

We assume that the governments are interested in maximizing a welfare function that consists of the consumer surplus for its local users plus all tax revenues generated on local and transit demand, net of investment costs associated with capacity provision. In the case of differentiated tolls the objective function for region A is given by:

(3) $$W_A = \int_0^{Y_A} (P_A^Y(y))dy - g_A^Y Y_A + t_A Y_A + \tau_A X - K_A \frac{1}{R_A}$$

where K_A is the unit cost of capacity expansion. This specification implies that we assume constant returns to scale in capacity extension throughout. Note that the same objective function is used for serial and parallel networks. The difference is situated in the demand functions (see above). Finally, note that (3) can easily be generalized to the cases of uniform tolls or local tolls only.

To analyze the two-stage pricing and capacity game in the next sections, it will be instructive to introduce simple functional forms for demand and cost functions.[3] Specifically, unless otherwise noted, we assume all demand and cost functions to be linear. Demands are given by:

$$P^X(X) = a - bX$$
$$P_i^Y(Y_i) = c_i - d_i Y_i$$
$$\text{with } a, b, c_i, d_i > 0, \text{ for } i = A, B$$

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

$$C_i(X + Y_i) = \alpha_i + \beta_i R_i (X + Y_i)$$
$$\text{where } \alpha_i, \beta_i > 0, i = A, B$$

[3] Note that these specifications will be used for all tax regimes considered as well, see below.

3 Toll and capacity competition in parallel and serial networks: the case of zero local demand

To set the stage, we start the analysis by considering a simplified case, viz. the case of zero local transport. In this case, there is no interaction between local and transit traffic, and tolling and capacity interaction between regions is easier to analyze.

3.1 Zero local demand: the serial case

Consider the simple case where there is no local transport on either of the two serial links. In fact, this may have some policy-relevance for small countries, where local transport on part of the network is almost negligible (for example, the highway passing through Luxemburg; some rail connections). Under those conditions, noting that transit demand is by definition equal in both regions, the cost functions for transport time (and resources) reduce to:

$$C_i(X) = \alpha_i + \beta_i R_i X \text{ , } i = A, B$$

Using the equilibrium conditions for transit, we then easily show that the reduced form transit demand is given by:

(4) $X^r = \dfrac{(a - \alpha_A - \alpha_B) - \tau_A - \tau_B}{N}$, where $N = b + \beta_A R_A + \beta_B R_B$

If local demand is zero, the objective function (3) for region A reduces to:

$$W_A = \tau_A X - K_A \frac{1}{R_A}$$

We solve the two-stage price-capacity game by backwards induction. First, consider the pricing game for given capacities. The first-order condition with respect to the price in region A is:

$$\tau_A \frac{\partial X^r}{\partial \tau_A} + X^r = 0$$

Solving for the tax rate in A immediately yields:

(5) $\tau_A = \beta_A R_A X + (b + \beta_B R_B) X$

Note that $\beta_A R_A X$ can be interpreted as the marginal external cost of congestion in region A. Then the optimal pricing rule (5) shows that the toll always exceeds the local marginal external cost. In fact, it implies more than that: the toll in region A covers more than the marginal external congestion cost in A plus the one in B. This phenomenon is similar to the issue of double marginalization in industrial organization (Tirole (1993)), Bresnahan and Reiss (1985)). It suggests that one expects relatively high tolls on transit in serial networks. Importantly, the optimal toll in A is also equally affected by congestion in A and B: the effect of an exogenous increase in $\beta_A R_A X$ is the same as for an increase in $\beta_B R_B X$. This follows from the serial network setting. Higher congestion in either A or B raises the generalized cost of the complete trip, hence has the same effect on transit demand. It therefore triggers the same price response in a given region.

Substituting the expression derived for X^r, equation (4), in the toll rule (5) and solving for the tax reaction function, we find:

$$(6) \quad \tau_A = \frac{a - \alpha_A - \alpha_B}{2} - \frac{1}{2}\tau_B$$

Two issues stand out. First, the reaction function is downward sloping in the toll charged by the other region. It implies that if one region raises its toll by one euro, then the overall toll on the whole trajectory increases by precisely 0.5 euro. This is a well known result in the vertical integration literature in industrial organization, where a cost increase at the downstream level is only partially reflected in final output prices. Second, the reaction function is independent of capacities and of congestion: it neither depends on the R_i, nor on the β_i. The reason is that regional congestion affects the toll in both regions equally. As a consequence, it does not affect the interaction in tolling behavior between the two regions.

Using the analogous expression for the tax rate in B and solving for the Nash equilibrium yields:

$$(7) \qquad \tau_A^{NE} = \tau_B^{NE} = \frac{a - \alpha_A - \alpha_B}{3}$$

The structure of this Nash equilibrium shows that the standard "double marginalization" result still holds in the presence of congestion. Moreover, it has powerful implications. It means that the only Nash equilibrium in tolls: (i) is symmetric, even if the free-flow cost parameters differ; (ii) is independent of capacities, and (iii) is independent of the slope of the congestion function, so that tolls are not used to control local congestion.

We now proceed to the first stage of the game, that is, the game in capacities. The first order condition for optimal capacity choice in region A is:

$$(8) \quad \tau_A^{NE} \frac{\partial X^r}{\partial R_A} - X \frac{\partial \tau_A^{NE}}{\partial R_A} + \frac{K_A}{R_A^2} = 0$$

The second term on the right hand side equals zero because the taxes are independent of capacities. Working out the derivative of expression (4) with respect to inverse capacity, substituting in (8) and using the definition of N, we find the capacity reaction function:

(9) $$\psi(R_A,R_B)=\beta_A\tau_A\left[\frac{\tau_A+\tau_B-(a-\alpha_A-\alpha_B)}{\left(b+\beta_A R_A+\beta_B R_B\right)^2}\right]+\frac{K_A}{R_A^2}=0$$

Using the implicit function theorem, the slope of the reaction function can be written as:

(10) $$\frac{\partial R_A^R}{\partial R_B}=-\frac{1}{\psi_{R_A}}*\left[-2\beta_B\beta_A\tau_A\left(\frac{\tau_A+\tau_B-(a-\alpha_A-\alpha_B)}{\left(b+\beta_A R_A+\beta_B R_B\right)^3}\right)\right]$$

where $\psi_{R_A}<0$ by the second order conditions for optimal capacity choice. It then follows that given optimal taxes, the reaction functions are unambiguously positively sloped. To see this, it suffices to use the Nash equilibrium tax expressions derived above so that $\tau_A+\tau_B-(a-\alpha_A-\alpha_B)<0$ follows.

Positively sloped capacity reaction functions make sense: optimal capacity choice by A implies equality between marginal capacity costs and marginal revenue of capacity expansion. Consider an increase in capacity in B. This certainly raises transit demand, hence (since taxes are independent of capacity) tax revenues in A. More importantly, however, given the demand function for transit derived above, it easily follows that the capacity change in B also raises the marginal revenue from an expansion in A. Given the constant marginal cost of capacity expansion, the increase in marginal revenue justifies a capacity expansion.

3.2 Zero local demand: the parallel case

The parallel case for zero local demand has been studied for revenue maximizing authorities by De Borger and Van Dender (2006), and De Palma and Proost (2006), although they do so in a somewhat different setting of competition between congestible private facilities. In our setting, using $C_i(X_i)=\alpha_i+\beta_i R_i X_i\,, i=A,B$ and noting that $X=X_A+X_B$, the equilibrium conditions can be solved for the demand functions for transit via A and B, respectively. We find:

(11) $$X_A^r=\frac{1}{M}\left[(a-\alpha_A-\tau_A)(b+\beta_B R_B)-b(a-\alpha_B-\tau_B)\right]$$

(12) $$X_B=\frac{1}{M}\left[(a-\alpha_B-\tau_B)(b+\beta_A R_A)-b(a-\alpha_A-\tau_A)\right]$$

where $M=b(\beta_A R_A+\beta_B R_B)+\beta_A R_A\beta_B R_B$

Consider the pricing game at given capacities. Solving the first-order condition for region A, $\tau_A\frac{\partial X_A^r}{\partial\tau_A}+X_A^r=0$, leads to the following rule:

$$(13)\quad \tau_A = \beta_A R_A X_A + \frac{b\beta_B R_B X_A}{b+\beta_B R_B}$$

A similar expression is derived for B. Since the first term on the right hand side is the marginal external cost of congestion, this states that the toll will exceed the marginal congestion cost. In a parallel structure, a higher toll in A raises congestion in the competing region B, making region A more attractive (Verhoef *et al* (1996), Van Dender (2005)). Note that investment and congestion now have different effects on tolling behavior, depending on where the investment takes place.

Using the expression for X_A (see equation (4)) in (13)), the toll reaction function for region A is readily obtained as:

$$(14)\quad \tau_A = \frac{Z_A}{2(b+\beta_B R_B)} + \frac{b}{2(b+\beta_B R_B)}\tau_B$$

where $Z_A = \beta_B R_B (a-\alpha_A) + b(\alpha_A - \alpha_B)$ is a function of demand and cost parameters. It follows that the reaction function is upward sloping. Moreover, both its slope and its intercept explicitly depend on capacity in the competing region. This contrasts with the serial case analyzed before.

Solving the reaction function and its counterpart for region B for the Nash equilibrium yields:

$$(15)\quad \tau_A^{NE} = \frac{2Z_A(b^2+M) + Z_B(b+\beta_B R_B)}{(3b^3+4M)(b+\beta_B R_B)}$$

$$(16)\quad \tau_B^{NE} = \frac{2Z_B(b^2+M) + Z_A(b+\beta_A R_A)}{(3b^3+4M)(b+\beta_A R_A)}$$

Simple differentiation of the Nash equilibrium tolls with respect to the shows that higher capacity in any given region induces both regions to reduce tolls. We have:

$$\frac{\partial \tau_A^{NE}}{\partial R_i} > 0, \quad i = A, B$$

In other words, a less congestible parallel network leads both competing authorities to reduce their tolls.

Unlike in the serial case, results for the capacity game are not straightforward. The dependency of tolls on capacities implies that the reaction functions in capacities implied by the first-order condition of the first-stage of the game, viz.

$$\tau_A^{NE}\frac{\partial X}{\partial R_A} - X\frac{\partial \tau_A^{NE}}{\partial R_A} + \frac{K_A}{R_A^2} = 0$$

are highly non-linear.It is shown in De Borger and Van Dender (2006) that this reaction function is plausibly downward sloping but that the nonlinearity implies the possibility of multiple equilibria. In fact, they show that asymmetric outcomes are more likely when unit capacity costs are low and/or structural transit demand is relatively inelastic. The interpretation of such an asymmetric equilibrium is quite intuitive. One region invests highly in capacity but also charges high tolls so that congestion is low. The competing region provides much less infrastructure but also charges low tolls so that congestion is much higher. Endogenously, toll and capacity competition induce regions to offer distinct packages, implying different "quality" levels at different "prices".

3.3 Zero local demand: summary and conclusion

Some tentative conclusions for the simple cases without local traffic are summarized in Table 1.

	Parallel links	**Serial links**
Toll reaction functions	Upward sloping: $\frac{\partial \tau_A}{\partial \tau_B} > 0$	Downward sloping: $\frac{\partial \tau_A}{\partial \tau_B} < 0$
Impact of capacity increase in A on tolls	More capacity reduces tolls: $\frac{\partial \tau_A^{NE}}{\partial cap_A} < 0, \frac{\partial \tau_B^{NE}}{\partial cap_A} < 0$	Tolls independent of capacities: $\frac{\partial \tau_A^{NE}}{\partial cap_A} = 0, \frac{\partial \tau_B^{NE}}{\partial cap_A} = 0$
Capacity reaction functions	Downward sloping: $\frac{\partial R_A}{\partial R_B} < 0$	Upward sloping: $\frac{\partial R_A}{\partial R_B} > 0$

Table 1: Characteristics of reaction functions and Nash equilibrium in the case of zero local transport

4 Tax and capacity competition in transport networks: Some general theoretical findings

In this section, we extend and summarize the main theoretical findings on tax and capacity competition in parallel and serial networks for the more realistic case with both local and transit demand on each link. The findings reported in this section are partly based on De Borger, Proost, Van Dender (2005) and De Borger, Dunkerley and Proost (2007). We extended the analysis for the parallel case to incorporate capacity choices using the same methodology as in the serial setting.

Since we limit the discussion here to a summary of the main findings, we refer to the papers mentioned for more details on their derivation. We proceed in several steps. We first briefly discuss the effects of tolls and capacities on the reduced-form demands for local and transit transport. These demands are the solution of the user equilibrium conditions (1) and (2) as a function of all tolls and capacities in both regions. We then discuss findings on the toll reaction functions in parallel and serial networks, and we report on what can be learned about strategic capacity choices.

4.1 The effect of tolls and capacities on transport demand

In tables 2a and 2b, we summarize the results that describe the effects of toll and capacity increases on the equilibrium demands for local and transit transport in both a parallel and serial setting (De Borger *et al* (2005, 2007)). Note that we assume interior solutions throughout; in the parallel case, this implies that both links are used in equilibrium.

Our findings are plausible and easily summarized. Firstly, although all own price effects are obviously negative, cross price effects depend in an intuitive way on network structure; routes are substitutes or complements depending on network design. For example, a toll on transit in region A raises transit demand in a parallel setting because transit shifts from A to B. Moreover, this in turn raises congestion in B, hence reduces demand for local traffic in that region. In a serial setting, however, higher tolls on transit in A reduce transit demand throughout the corridor; the decline in congestion in B then raises demand for local transport in that region. Similarly, in a parallel setting, raising local tolls in A attracts transit to A, hence reduces transit demand in B. It therefore raises local demand in B because of declining congestion. In a serial network, the same toll increase in A raises transit through B, hence reduces local demand there.

	Effect on transit demand in A	**Effect on transit demand in B**	**Effect on local demand in A**	**Effect on local demand in B**
Toll on transit in A	<0	>0	>0	<0
Toll on local demand in A	>0	<0	<0	>0
Uniform toll on both local demand and transit in A	<0	>0	<0	<0
Capacity increase in A	>0	<0	>0	>0

Table 2a: Demand effects of tolls and capacity investment in parallel networks (effects of toll or capacity changes in one region on demand, holding all other tolls and capacities in both regions constant)

Next, consider the impact of capacity investments on demand. Again, results differ according to network design. Capacity investments in A raise demand for both transit and local demand in A but the impact on demand in B depends on network structure. A serial setting yields more transit through B, hence less local demand there; a parallel setting shifts transit from B to A and raises local demand in B because of lower congestion.

	Effect on transit demand in A and B	**Effect on local demand in A**	**Effect on local demand in B**
Toll on transit in A	<0	>0	>0
Toll on local demand in A	>0	<0	<0
Uniform toll on local demand and transit in A	<0	<0	>0
Capacity increase in A	>0	>0	<0

Table 2b: Demand effects of tolls and capacity investment in serial networks (effects of toll or capacity changes in one region on demand, holding all other tolls and capacities in both regions constant)

Note: Transit demand in A equals that in B by definition.

4.2 Strategic tolling behavior

In this sub-section, we summarize what can be learnt about the tolling behavior of countries under different network structures. We first describe the optimal toll rules in a given region, at given capacities and for given tolls set by the other region. Next, we describe the characteristics of the toll reaction functions. For differentiated tolls, the government in region A optimises the objective function given by (3), with respect to t_A, τ_A. The generalization of (3) to the other toll regimes follows directly. Note that the demand functions entering the objective function are different for the parallel and serial networks.

The optimal toll rules are derived in De Borger *et al* (2005, 2007). Interestingly, they are the same for parallel and serial settings, although (see below) they have very different practical implications depending on the network structure. The toll rules imply tax exporting behavior: if regions can differentiate tolls between local and transit demand, then they will toll transit at a higher rate than local demand; if tolls are restricted to be uniform, then the optimal toll positively depends on the importance of transit.[4] Moreover, the use of local tolls strongly depends on the instruments available. If transit can be tolled, then tolls on local traffic are set higher than the local marginal external congestion cost in order to reduce congestion on the local link, hence indirectly attract more transit (tax competition

[4] There is some scarce empirical evidence that supports these theoretical predictions. For example, Nash (2005) reports very high rail rates in Switzerland and in former communist countries of the EU (for example Slovakia), pointing at double marginalization as a possible explanation. His findings also suggest a relation between the share of transit and the level of infrastructure charges on European rail links. Moreover, he warns that levels of charges may be prohibitively high for international traffic involved in transit of a country. Also see Bassanini and Pouyet (2005).

for transit). If, however, local tolls are the only instrument, then these tolls are set below local marginal external cost. The reason is that by doing so, regions reduce transit demand; the latter generates congestion and does not contribute to either welfare or tax revenues.

The optimal toll rules for a given region implicitly describe the toll reaction functions. To illustrate the importance of network structure for strategic behavior by regions in the simplest possible way, it is instructive to return to the case of linear demands and costs, presented in section 3 above. In the serial case, and focusing on differentiated tolls for local and transit transport, the reaction functions can then be shown to have the following structure (De Borger *et al* (2007)):

$$(17)\quad \tau_A = c_A^\tau - (\frac{1}{2})\tau_B - (\frac{1}{2}z_1^B)t_B$$

$$(18)\quad t_A = c_A^t + (\frac{1}{2}L^A)\tau_B + (\frac{1}{2}z_1^B L^A)t_B$$

where the parameters c_A^τ, c_A^t, z_1^B and L^A are all functions of demand and cost parameters. Moreover, z_1^B (where $z_1^B < 0, \left|z_1^B\right| < 1$) gives the effect of an exogenous increase in transit transport in region B on the demand for local transport in that region. Finally, $-1 < L^A < 0$. Note that in the absence of local demand these expressions are consistent with the results described in section 3. To see this, compare (17) with (6).

The interpretation is clear. We find that an increase in the transit tax in B induces region A to optimally reduce both its transit tax and the tax on local traffic. The higher tax on transit in B reduces transit demand, hence reduces congestion in A. The optimal response in A is therefore to reduce both taxes. Similarly, a higher local tax in B induces region A to optimally raise transit as well as local taxes in A. The higher local tax in B reduces congestion in B and attracts more transit. This also raises congestion in A. Therefore, country A raises its tax rates on all traffic on its territory.

The structure of the reaction functions for the parallel links are quite similar. We derived elsewhere (De Borger *et al* (2005)):

$$(19)\quad \tau_A = d_A^\tau - (\frac{1}{2}\delta)\tau_B - (\frac{1}{2}\delta z_1^B)t_B$$

$$(20)\quad t_A = d_A^t + (\frac{1}{2}\delta K^A)\tau_B + (\frac{1}{2}\delta z_1^B K^A)t_B$$

where the coefficients depend on demand and cost parameters and:

$$\delta < 0, \quad 0 < \left|\delta\right| < 1$$
$$-1 < K^A < 0$$

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 local 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.

What do we learn from these reaction function specifications? Firstly, comparing parallel and serial cases, we see that the slopes of the reaction functions are of opposite signs, as one would expect. Secondly, in setting transit tolls regions react more strongly to toll changes abroad in serial networks than in parallel settings. This follows from $|\delta|<1$. It implies that one expects more tax competition and tax exporting behavior on serial networks than on parallel networks. Finally, the strongest interaction between regions is in the transit tolls. Changes in local tolls have much less effect on other regions. In fact, the strategic interaction in local tolls is almost negligible. Economically, it makes sense. Local tolls only affect local tolls abroad via their impact on congestion and the shift in transit to the other region but there is no direct tax competition as in the case of transit.

4.3 Capacity reaction functions

Unfortunately, few general theoretical results could be derived on the nature of capacity competition, largely due to the complexity of the dependency of Nash equilibrium tolls on capacities in both regions. However, the few theoretical results as well as findings based on numerical work (see, among others, De Borger *et al* (2007), De Borger and Van Dender (2006)) lead to the following predictions. When we consider the effect of capacity changes at the first stage on the Nash equilibrium tolls at the second stage, in a serial setting, capacity increases in region A reduce Nash equilibrium tolls on both transit and local demand in A. In B, it will lead to more congestion, therefore higher tolls. In a parallel network, we see the opposite. A capacity increase in A leads to toll reductions there because of lower congestion but congestion in B will also be reduced, hence reducing tolls. Further, with regard capacity reaction functions, we see that in serial networks, capacities are strategic complements: capacity reaction functions are plausibly upward sloping. More capacity in A raises congestion in B, inducing this region to raise capacity as well. Parallel settings imply, on the contrary, that capacities are likely to be strategic substitutes: capacity reaction functions are plausibly downward sloping. More capacity in a region attracts transit from the other region, reducing the capacity requirements in that region. So the predictions reported in Table 1 for the case of zero local demand are likely to generalize to the situation with both transit and local demand.

5 Numerical illustration

This section presents some illustrative results based on numerical simulation analysis that allow us to compare the nature and extent of toll and capacity competition on simple serial and parallel networks. We first describe the calibration of the numerical illustration (subsection 5.1). Then we proceed to discuss the price setting and investment behavior in the serial and parallel case. We consecutively analyze the efficiency of the zero toll Nash equilibrium capacity choices (subsection 5.2), the desirability of allowing the tolling of transit by differentiated or uniform tolls (subsection 5.3), and the welfare effects if only local transport can be tolled (subsection 5.4). Finally, we report results for the solution that would be welfare maximizing from the viewpoint of a federal authority that coordinates the whole network. Throughout, the focus is on the importance of the different network structures for the results.

5.1 Calibration of the reference case

We have chosen a numerical example with a maximum of comparability between the parallel and the serial network. For the sake of clarity, we limit ourselves to the symmetric case with two identical regions. The calibration process starts with the reference data for the serial case given in the lower left part of table 3.

	Serial	Parallel
Demand function local	$P^Y = c - dY$, where *c=283.6* and *d=0.17*	
Demand function transit	$P^X = a - bX$, where *a=567.1* and *b=0.33* ($X = X_A = X_B$)	$P^X = \frac{a}{2} - \frac{b}{4}(X_A + X_B)$
Congestion function	$C_i = \alpha + \beta R_i V_i$ for $i = A, B$, where $V_i = X_i + Y_i$, and $\alpha = 34.3$ and $\beta = 23.9$	
Cost of capacity	*K=18.7*	
Reference equilibrium = the zero toll equilibrium at optimal capacity	*Y = 1300*, $P^Y = 65$ *X = 1300*, $P^X = 130$ Capacity (=1/R) = 2000	*Y = 1206*, $P^Y = 81.3$ *X = 1206*, $P^X = 81.3$ Capacity *(=1/R) = 1229*

Table 3: Calibration of the numerical example

Note: Endogenous elements are in italics.

The model is initially calibrated with zero tolls. We choose local and transit flows that have a similar order of magnitude; moreover, reference time costs are of the same order of magnitude as the non time costs. The level of congestion in the reference equilibrium is such that the time costs are 50% higher than at zero traffic. This yields a generalized cost and a time cost in the reference equilibrium, as well as two points for the congestion function so that the intercept α and the slope (which at constant capacity equals βR) can be determined. To complete the calibration of the demand functions, we have chosen an elasticity of local demand equal to -0.3. Finally, reference capacity is fixed at 2000. Since *R* is inverse capacity this, together with the slope of the congestion function, determines β.

In order to facilitate the comparison with the other regimes that will be studied, it is assumed that the chosen capacity (2000) in the zero toll serial case is the Nash equilibrium for each of the regions. This is done by determining the cost of capacity extension K in such a way that this indeed holds. This completes the calibration of the serial network case.

5.2 How efficient is capacity competition in the zero toll reference case?

The most relevant results for the different regimes and for the two different network structures are summarized in Table 4. First, consider the no-toll case. As noted before, this case has been used for the calibration and serves as reference here. We see that there remain, both in the serial and parallel networks, important marginal external congestion costs that are not internalized. For example, in the serial case, the local and global marginal external congestion costs equal 15.6 and 31.1, respectively. Note that the term "local" refers to the marginal external congestion cost imposed on local users; "global" refers to the overall cost imposed on local users and on transit. An important property of the serial case that was referred to in the theoretical sections of the paper but that is not apparent from this table, is that the capacity levels are strategic complements: whenever one region increases capacity, the other has an interest to follow in order to cope with the increased transit flow. In the parallel case, capacities in the two regions are strategic substitutes. We see that although flows would be identical for identical capacity, the Nash equilibrium has a much lower level of capacity. Indeed, whenever a region (say A) increases its capacity it attracts extra transit from the other region. Making route A initially cheaper results in arbitrage over the network that produces strong disincentives to increase capacity in the first place.

5.3 Is allowing differentiated tolling welfare improving?

Economists have often advocated the use of tolling instruments to cope with non-internalized congestion. In principle, one can allow differentiated (between local and transit transport) or uniform tolling. Both cases are considered in Table 4, for the serial and parallel network structure. In the serial case, the Nash equilibrium results show that allowing regions to toll all transport on their network (whether by differentiated or uniform tolls) implies a decline in total welfare, that is, it makes things worse compared to the no tolling case. Overall welfare decreases by 13% to 20% in the uniform and differentiated cases, respectively. Note that overall welfare reported in the table refers to the welfare of all network users; it includes both the welfare of local and of transit users. The reason for the welfare decline is related to the double marginalization behavior referred to before. It occurs because the two "monopolists" do not coordinate their price setting of transit transport. As a consequence, we find very high margins on transit in the differentiated toll case; they are well above the marginal external congestion cost. In the uniform case, it results in high tolls on all transport on the network. These high prices allow savings on capacity costs with optimal capacity substantially lower than in the no toll reference situation. However, these savings do not compensate for the losses in consumer surplus, especially for transit users.

In the parallel case, we find the opposite results. Introducing tolling allows the low investment incentives of the no toll case to be overcome and this gives much higher capacity levels (about 2180 compared to 1229 in the zero toll reference). Optimal tolls are positive but as predicted by the theory presented earlier, transit tolls are much lower than in the serial case. This holds both for differentiated and uniform tolls. The consequence of much lower Nash equilibrium tolls on transit implies that in the parallel case overall welfare rises substantially.[5]

5.4 Welfare effects of tolling local traffic only

Consider the results for the case where, for whatever reason, transit remains un-tolled. When only local traffic can be tolled, one obviously rules out tax exporting. Contrary to the cases where transit was tolled, this implies that on a serial network small welfare improvements are now attained compared to no tolling at all. The toll is slightly below local marginal external cost, and the toll somewhat reduces demand so that a lower capacity is optimal compared to the zero toll case (1945 compared to 2000). In the parallel case, the welfare benefits are positive as well because one can achieve a better use of the network by the local traffic and save some capacity costs. However, as only part of the traffic is actually controlled, the welfare gains that can be achieved remain very small. Also, observe that the optimal local toll is smaller than in the serial case. The reason is that the purpose of the local toll is to indirectly control transit as well as local traffic. Reducing transit by local tolls requires higher tolls in the serial case because transit demand through any given region is only affected via increases in congestion. The reaction of transit is stronger in the parallel case because, unlike in a serial corridor, an alternative route is available.

5.5 The ideal solution for a federal government: the first-best

Finally, we move away from tax and capacity competition between the two hypothetical regions. Instead, we assume that the whole network is under the control of one “federal” government; it decides on tolls and capacity investments for the network by maximizing overall welfare for all users of the whole network.

The results are reported in the final two columns of Table 4. Firstly, at this federal optimum tolls are set equal to the global marginal external congestion cost that takes account of the time losses imposed on both transit and on local traffic. Note that, although tolls can in principle be differentiated, there is no need to do so; the tolls on local and transit transport are equal at the optimum. Secondly, capacity levels are chosen simultaneously in each region such that the marginal cost of capacity extension equals the marginal benefit for all transport, transit and local. Thirdly, note that except for rounding errors in the calculations, the optimum solutions for the parallel and serial networks are identical. This is due to the fact that the zero toll cases for both network types were calibrated using the same local demand functions, the same values of time, the same congestion functions and the same costs of extra capacity. Finally, given that the federal optimum yields identical tolls, capacities, demands and overall welfare levels for the two network types, the welfare improvement in the parallel case is much more important than on the serial network. This follows from the lower welfare level in the zero toll case for the parallel network.

[5] Even if the capacity levels would be kept at the zero toll case (not shown in table 4), we found that allowing tolling would be beneficial. The gains of a better use of a given capacity are important and abuse of a monopoly position by one region is limited by the Bertrand competition with the other region.

Variable	Unit	No tolls		Nash Equilibrium differentiation		Nash Equilibrium uniform		Nash Equilibrium local tolls only		Centralised differentiation	
		serial	parallel	serial	parallel	serial	parallel	serial	parallel	serial	Parallel
Local demand	Trips	1300	1206	1219	1184	732	1131	1215	1149	1233	1232
Transit demand	Trips	1300	1206	396	1122	732	1131	1301	1207	1233	1232
Trip volume (country)	Trips	2600	2411	1616	2306	1465	2261	2516	2355	2467	2465
Local MEC	Euro /Trip	15,6	23,5	16,8	13,0	10,8	12,4	14,9	22,8	10,6	10,6
Global MEC	Euro /Trip	31,1	46,9	22,3	25,3	21,7	24,8	31,0	46,8	21,1	21,2
Local Toll	Euro /Trip	0	0,0	22,3	25,3	104,7	34,7	14,4	9,7	21,1	21,2
Transit Toll	Euro /Trip	0	0,0	160,4	35,6	104,7	34,7	0,0	0,0	21,1	21,2
Capacity	Trips	2000	1229	1732	2179	1618	2179	1945	1205	2791	2778
Local CS	Euro	141779	121929	124726	117517	45011	107257	123815	110729	127602	127403
Tax revenue (country)	Euro	0	0	90793	69938	153333	78410	17536	11129	52160	52318
Overall welfare	Euro	492348	441783	392658	504750	426209	504402	493956	442952	510409	510407
Welfare change compared to the case of no tolls	%	0	0	-20,25	14,25	-13,43	14,17	0,33	0,26	3,67	15,53

Table 4: Results from serial and parallel networks – symmetric model with 50% transit, tolls and capacity optimal

Note: Transit share in No tolls system is 50 %. The distinction between countries is eliminated because results are symmetric.

Summarizing the first-best outcome, marginal external cost pricing and optimal capacity choice for the network as a whole yield much higher benefits in a parallel structure than in a serial setting. Note that the welfare improvements, even for the parallel case, seem rather modest: some 15% compared to the reference situation. This is, however, due to the fact that the reference itself was calibrated such that it corresponds to the Nash equilibrium with zero tolls but optimal capacity choice.

5.6 Summary of the numerical comparison

In Tables 5a and 5b, we summarize the main implications of the numerical findings. We observe clear differences in the extent and the nature of tax competition (very severe in the serial case) and capacity competition (very severe in the parallel case). Moreover, welfare benefits differ according to network structure.

	% Welfare change	% Capacity change	Transit toll	Conclusion
First-best federal optimum	+3.67	+40	Toll=MECC	Higher capacity and positive tolls
Nash toll discrimination	-20.25	-13	Toll much larger than MECC	Lower capacity and very high transit tolls; severe toll exporting (double marginalisation); tolling reduces welfare
Nash uniform toll	-13.43	-19	Toll much larger than MECC	Lower capacity and high uniform tolls; severe toll exporting (double marginalisation); tolling reduces welfare
Toll on local demand only	0.33	-3	Toll zero	Lower capacity because it mainly benefits transit

Table 5a: Summary of findings serial case (% changes are relative to the references case without tolling)

	% Welfare change	% Capacity change	Transit toll	Conclusion
First-best federal optimum	+15.53	+125	Toll=MECC	Much higher capacity and positive tolls
Nash toll discrimination	+14.25	+77	Toll somewhat larger than MECC	Much higher capacity and higher transit tolls; tolling raises welfare
Nash uniform toll	+14.17	+77	Toll somewhat larger than MECC	Much higher capacity and higher transit tolls; tolling raises welfare
Toll on local demand only	0.26	-2	Toll zero	Lower capacity because it mainly benefits transit

Table 5b: Summary of findings parallel network (% changes are relative to the references case without any tolling)

6 Conclusions

The purpose of this paper was to provide a theoretical and numerical comparison of the toll and capacity competition to be expected on serial and parallel transport networks when regional governments set user charges and determine capacities. Although the networks were very simple, some interesting results could be derived. When deciding on transit tolls, regions react more strongly to toll changes abroad on serial networks than in parallel settings. Moreover, tolls on transit are much higher in serial than in parallel settings, reflecting less elastic transit demand and double marginalization. On a serial corridor, whenever one region increases capacity, the other has an interest to follow in order to cope with the increased transit flow. In the parallel case, we see the opposite, resulting in lower Nash equilibrium levels of capacity. Arbitrage between routes acts as a strong disincentive to increase capacity in this case.

The welfare effects of allowing tolling of transit are drastically different, depending on the network structure. In the serial case, the results show that allowing regions to toll all transport on their network (whether by differentiated or uniform tolls) implies a decline in total welfare. Compared to the zero toll case, we found that overall welfare decreased by 13% to 20% for uniform and differentiated tolls, respectively. The reason for the welfare decline is due to double marginalization. As a consequence, we find very high margins on transit in the differentiated toll case; they are well above the marginal external congestion cost. These high prices allow savings on capacity costs with optimal capacity substantially lower than in the no toll reference situation. However, these savings do not compensate for the losses in consumer surplus, especially for transit users. In the parallel case, we find the opposite results. Introducing tolling allows the low investment incentives to be overcome in comparison with a situation where regions do not toll transit at all, yielding higher capacity levels. In combination with much lower Nash equilibrium tolls on transit than in the serial setting, this implies that in the parallel case overall welfare substantially rises when regions are allowed to toll all traffic. Note that, if only local transport can be tolled, there is a welfare increase on both types of networks. However, as only part of the traffic is actually controlled, the welfare gains that can be achieved remain very small.

This paper has clear policy implications. The European Commission is actually capping the user tolls on motorways to the average infrastructure costs; the main motivation for this was the potential abuse of monopoly power. Our analysis suggests that it would indeed be very damaging for European welfare if the EU were to let individual countries freely decide on tolls on the links of the serial TEN-Ts they control. From this perspective, restricting the tolls countries can charge is good policy. However, although restricting tolls seems indeed justified, the tolls should be allowed to reflect external congestion costs and not be based on average infrastructure costs. Moreover, our analysis of capacity decisions on transport networks where transit cannot be tolled point to capacities being too low. This should be an important element in a federal infrastructure subsidy program. The results suggest that it may be a good idea to relate the provision of subsidies to the importance of transit flows and to the introduction of marginal social cost pricing.

We conclude our analysis by drawing attention to three caveats. We have assumed constant returns to scale in capacity extension throughout. This may not be realistic for modes such as rail and inland waterways, and the the modeling of the capacity decisions may have to be adjusted (see De Borger, Dunkerley and Proost, 2008). The second caveat is that we only examined proportional pricing solutions. It is well known that two-part pricing and more generally, non linear pricing, can extract a larger share of the user surplus. Non-linear pricing exists (Eurovignettes or motorway vignette to cross Switzerland) but in our model, setting it would require a specification of the different user classes and their demand functions to reach firm conclusions. Finally, we assumed a straightforward objective function for the regional government and a simple non cooperative behavioral setting to derive conclusions. It remains to be tested whether our propositions can be falsified.

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