Is the travel time of private roads too short, too long, or just right?†

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Abstract

We consider price and service-quality setting in oligopolistic markets for congestible services, applied to the case of private roads. Previous studies show that parallel competitors set a volume/capacity ratio (and thereby a travel time or service quality) that is socially optimal if they take the actions of the others as given. We find that this result does not hold when capacity and toll setting are separate stages—as then firms aim to limit toll competition by setting lower capacities, and thus higher travel times—or when firms set capacities sequentially, as then firms aim to limit their competitors’ capacities by setting higher capacities. In our Stackelberg competition, the last firm to act has no capacity decisions to influence. Hence, it is only concerned with the toll-competition substage, and sets a travel time that is longer than socially optimal. The first firm cares mostly about the competitors’ capacities that it can influence: it sets a travel time that is shorter than socially optimal. The average travel time will be too short from a societal point of view.

JEL codes: D43; D62; L13; R41; R42
Keywords: Private Road Supply, Oligopoly, Stackelberg Competition, Service Quality, Optimal Travel Time

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1. Introduction

As government budgets become increasingly tight, it becomes ever harder to find funds to build or expand infrastructures in the face of ever growing demand. This has sparked a rising interest in private supply of such infrastructures, often supported by the popular view that private firms operate more efficiently because of their profit motive, thereby lowering the cost of capacity. We investigate the effects of private supply of congestible facilities—such as roads, airports, waste disposal, energy networks, and telecommunication—in different oligopolistic markets on welfare, profits, and in particular on service quality. We focus on the case of private roads, where service quality is measured by the travel time. However, our analysis and market structures could be applied to any congestible facility.

In Western Europe, about a third of the motorways is privately owned (Verhoef, 2007). In the USA, private roads and express-lanes are becoming increasingly common (see Winston and Yan (2011, p. 993) for a short discussion); the same is true for many developing countries. Hence, private roads form an important and relevant option in contemporary transport policy.

Yet, there are also disadvantages of private supply of congestible facilities. Invariably the private operator has market power: it is after all impossible to have an infinite number of (parallel) competing roads (or, alternatively, airports or waste-disposal sites), as required for a perfectly-competitive outcome. Hence, firms can be expected to set prices and capacities that are profit-maximising, but not socially optimal. Important questions are how harmful this is for social welfare, and to what extent the answer depends on the number of firms.

The early literature on private roads looked at toll setting by a monopolist on a road of given capacity (please see Table A.1 in the appendix for a structured overview of the toll and capacity rules of the papers mentioned in the introduction). When users are homogeneous and demand is not perfectly elastic, the monopolist generally sets a higher toll than the socially optimal one, and has consequently less congestion, shorter travel times and thus a higher service quality (see, e.g., Buchanan, 1956; Mohring 1985).

But this argument ignores capacity setting. Xiao, Yang and Han (2007) study private firms that build and operate parallel roads between a single origin and destination. Firms simultaneously determine capacity and tolls while taking the actions of the other as given: i.e. there is a single Nash-competition stage (also called an open-loop game in the literature). In this case, firms set the socially optimal travel time: that is the travel time that minimises the sum of user cost and infrastructure cost. Thus, private supply does not lead to a distorted choice of quality. Nevertheless, firms do set higher tolls, build lower capacities, and have fewer users than is socially optimal. Wu, Yin and Yang (2011) extend this work by showing that also when firms compete in a general network they set the socially-optimal travel time, if they take the actions of the others as given.

The crucial assumption behind the above results is that capacities and tolls are set simultaneously. De Borger and Van Dender (2006) use separate Nash-competition substages for capacity and toll (i.e. Two-substages Nash, or a closed-loop game). Now, firms set a capacity that implies a travel time that is longer than socially optimal, as this lessens toll competition and increases equilibrium tolls. This is opposite to the finding of the earlier literature, which emphasised shorter travel times due to private tolling on fixed capacities.
Separate stages for capacity and toll seem more realistic, as it takes a considerable time to build or expand a road, whereas the toll could be changed at virtually any moment. However, the two substages Nash set-up still assumes that all firms build their roads simultaneously. This also seems an unrealistic assumption. Obviously, in reality, roads are not constructed all at the same moment. When firms play a sequential capacity game, “earlier” movers are unlikely to take the actions of “later” movers as given, and the firms will not compete in a Nash fashion.

To take this into account, we consider firms first setting their capacities sequentially in a Stackelberg fashion, and then simultaneously setting tolls in a Nash fashion. Nash setting of tolls seems most realistic, as tolls can be changed frequently and it is hard to credibly commit to a toll level. Now, a firm faces 2 conflicting goals: (1) by setting a larger capacity, it can induce firms that follow to set lower capacities, which increases its market power and profit; (2) by setting a lower capacity, it will face weaker toll competition and thus get a higher profit. The first firm to enter sets a higher capacity than it would choose without these strategic considerations, and this means that its travel time is shorter than socially optimal (or alternatively that service quality is higher). The last firm to enter has no capacities to affect. Hence, it cares only about the toll substage, and sets a lower quality than socially optimal. Other firms set qualities that are in between these two extremes; and the quality is higher, the earlier the firm sets its capacity. We will see that in our numerical model, with two firms, the first firm offers a higher than socially optimal quality, and the second a lower quality. With five firms, the first three firms have a higher quality, and the last two a lower one. Most importantly, on average, the quality on the private roads is too high from a societal point of view. Still, welfare can be higher under our Stackelberg setting than under Nash-competition: Stackelberg competition increases the leaders’ market power, but also tends to increase total capacity and to decrease the average toll.

2. Analytics
2.1. Basic policies
Consider a case where there are multiple roads connecting a single origin and destination. Generalised user cost, $c_i$, (or user cost for brevity) of link $i$ is homogeneous to the degree zero in the number of users, $q_i$, and the capacity, $s_i$. Hence, user cost, marginal external cost, as well as the travel time, only depend on the volume/capacity ratio $q_i/s_i$. We indicate total capacity by $S$, and total number of users by $Q$. Marginal external cost is the external cost imposed on other users. We assume that the derivative of user cost with respect to the number of users is always positive; and that with respect to capacity it is always negative.

We assume that users have homogeneous preferences. Capacity is a continuous variable, and its cost is proportional to capacity and follows $c^{S,i} = k \cdot s_i$. Throughout the paper, we assume that demand is price sensitive. Moreover, all roads are congestible, and have the same

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1 For instance, on the I-15 in California, the toll can be changed every six minutes (Brownstone et al., 2003); whereas the tolls on the I-91 in California and in Singapore are updated every 3 months (www.onemotoring.com.sg/publish/onemotoring/en/on_the_roads/ERP_Rates.html and http://infopedia.nl.sg/articles/SIP_1386_2009-01-05.html accessed on 7 June 2011).

2 A firm might make a contract with the government or a consumer organisations. But it seems unlikely that such partners would sue for breach of contract when the firm lowers its toll, making this commitment not credible.
congestion and construction technologies, and are perfectly divisible. Finally, we ignore that private firms might work more (in)efficiently than the government: both have the same capacity costs, and toll collection cost are zero for both.

We first discuss some basic policies that act as benchmarks for the oligopolies. Since these policies are conventional in the literature, we will keep the discussion short; for a more detailed discussion please see, among others, Small and Verhoef (2007). In all policies, except the First-best (FB) one, part of the capacity remains untolled.

In the First-best (FB) case, the toll, \( \tau_{FB} \), equals the marginal externality, and capacity is set such that the marginal cost of capacity expansion, \( k \), equals the reduction in total user cost, \( -c_s \cdot Q \), that it achieves:

\[
\begin{align*}
\tau_{FB} &= c_Q \cdot Q, \\
k &= -c_s \cdot Q
\end{align*}
\]

Note that we use subscripts to indicate partial derivatives; superscripts indicate the market regime or road.

If a certain initial capacity, \( s^0 \), remains untolled while the new public capacity, \( s^1 \), can be tolled, we are in a second-best (SB) situation. The SB toll has a term that equals the externality on the tolled road, \( c_q \cdot q^1 \), and a negative term to attract users away from the untolled road:

\[
\tau_{SB} = c_q^1 \cdot q^1 - c_q^0 \cdot q^0 \left( \frac{-D_0}{c_q^0 - D_Q} \right).
\]

The \( D_Q \) is the derivative of inverse demand to the number of users; \( q^0 \) and \( q^1 \) are the number of users on the initial and new road. In equilibrium, inverse demand equals the sum of user cost and toll (i.e. the generalised price, or price for brevity). While the toll rule is adapted to reflect the second-best distortion, the capacity rule remains (basically) the same. It states that the cost of a marginal capacity expansion equals the user cost reduction on the priced link it achieves:

\[
k = -c_s^1 \cdot q^1.
\]

Due to the assumptions that \( c^j \) is homogeneous to the degree zero in \( q^j \) and \( s^j \) and that \( c_q^1 > 0 \) and \( c_s^1 < 0 \), the terms \( c_q^1 \cdot q^1 \) and \( c_s \cdot Q \) only depend on the relevant volume/capacity ratio (\( q^j/s^j \) or \( Q/S \)). Since \( c_q^1 \cdot q^1 \) in (4) and \( c_s \cdot Q \) in (2) both equal \( k \), this implies that the volume/capacity ratio must be the same on the tolled SB link as on the entire FB network. But since there also is the untolled road, the average volume/capacity ratio for the entire SB network is higher.

Also a Single firm (SF) offering capacity in parallel to an untolled road uses the capacity rule (4), and hence has the same volume/capacity ratio on its road.\(^3\) Any decrease in user costs can

\[^3\] That the single firm sets the socially optimal quality should come as no surprise as it follows the result of Spence (1975), who finds that a monopolist sets the socially optimal quality if \( \partial^2 D/\partial Q \partial \theta > 0 \) (where \( \theta \) is the quality), which is the case in our model. Whereas, if \( \partial^2 D/\partial Q \partial \theta > 0 \) (\(<0\)), it sets a too high (too low) quality. If capacity costs were increasing in total capacity, the single firm would still set the socially optimal quality given the number of users. But, because total capacity is lower, it has a lower marginal capacity cost, and thus sets a lower ratio than in the first-best case. For decreasing costs, the reverse reasoning holds.
be converted into toll payments, so, for a given number of users, it is profit maximising to minimise social cost by using the same capacity rule as in the SB case. But the toll of the single firm is higher, as, following equation (5) below, the firm adds a mark-up to the congestion-externality charge as long as demand is not perfectly elastic (i.e. \(-D_Q > 0\)) and as long as the untolled road is congestible (i.e. \(c^0_{q_0} > 0\)).

\[
\tau_{SF} = c^1_{q_1} \cdot q^1 + q^0_{c_0} \cdot c^0_{q_0} \left( -\frac{D_Q}{c^0_{q_0} - D_Q} \right)
\]

(5)

The firm internalises the congestion externality, as any reduction in user cost can be skimmed off by a toll increase. The capacities in the single-firm and second-best cases are generally different: the higher private toll means that there are fewer users, which, for an equal ratio, means that the capacity of the single firm is lower. Concluding, the quality set by the single firm is socially optimal, whereas the choice of toll is distorted by market power.

The SB case makes a loss that can be very large, which may be hard to finance by the government. Therefore, we look at welfare maximisation of a road under a zero profit constraint with a parallel untolled road (Second-best zero profit or SBZP). This case is a useful benchmark, as we will see that the oligopolies approach it as the number of firms increases. Note that this set-up is equivalent to an untolled road with parallel private firms in perfect competition (see Verhoef, 2008). We use this set-up as the benchmark for the oligopolies, as it is the most efficient an oligopoly could approach, when there is unpriced parallel capacity. The First-best outcome the oligopolies cannot attain as there is the fixed untolled capacity that we allow for, the second-best outcome cannot be attained since it makes a large loss.

The corresponding Lagrangian is

\[
\Lambda_{SBZP} = \int_0^T D(n)dn - q^0 \cdot c^0 - q^1 \cdot c^1 - k \cdot s^1 + \lambda^1 \left( D[Q] - c^0 \right) + \lambda^1 \left( D[Q] - c^1 - \tau^1 \right) + \lambda^P \left( \tau^1 \cdot q^1 - k \cdot s^1 \right).
\]

To find the capacity rule, we only need the first order conditions for toll and capacity:

\[
\frac{\partial \Lambda_{SBZP}}{\partial \tau^1} = 0 = -\lambda^1 + q^1 \cdot \lambda^P,
\]

(6a)

\[
\frac{\partial \Lambda_{SBZP}}{\partial s^1} = 0 = -q^1 \cdot c^1_{s} - k - \lambda^1 \cdot c^1_{s} - k \cdot \lambda^P.
\]

(6b)

Eq. (6a) implies \(\lambda^1 = q^1 \cdot \lambda^P\), and inserting this into (6b) results in the capacity rule:

\[
k = -c^1_{s} \cdot q^1.
\]

(7)

Hence, the ratio is again socially optimal. Interestingly, the toll follows the same formula as the First-best toll:

\[
\tau_{SBZP} = c^1_{q} \cdot q^1.
\]

(8)

The intuition behind this result can be understood by linking it to the self-financing (i.e. zero-profit) result of Mohring and Harwitz (1962), which states that under FB pricing and capacity

\[4\] Conversely, in Knight (1924) the firm does not add a mark-up because he assumes \(c^0_{q_0} = 0\) (i.e. that the untolled road is uncongestible and thus its marginal cost is constant).
setting, the revenues from pricing equal capacity cost (when there are neutral scale economies in road construction, as is the case in this model). Since, the volume/capacity ratio is the same as with FB pricing, the FB toll rule also leads to zero profit here. Eq. (8) also implies that the levels of the tolls are the same. In both cases the toll equals the congestion externality, which is a function of the ratio only. Thus, if the ratios are the same, the tolls will also be the same.

With price-sensitive demand and congestible capacity, the toll is now higher than in the SB case, and thus there are fewer users and capacity is lower. At the same time, the toll is lower than the one the single firm sets.

2.2. Single-stage Nash

For all our oligopolistic regimes, we assume that some initial capacity remains untolled, and this will limit the market power of the firms. This set-up seems realistic for many practical cases—and of course a zero unpriced capacity is just a special case of our model.

Our first oligopolistic game is Single-stage Nash as considered by Xiao et al. (2007). Firms set their capacities and tolls simultaneously. If firms take the tolls and capacities of the others as given, they set the socially-optimal volume/capacity ratio. At this ratio, the cost of a marginal capacity expansion equals the reduction in total user cost on this link it causes. If the firm offered a higher capacity this would reduce user costs and it could ask a higher toll, but then the extra revenue would be smaller than the extra capacity costs. Note that firms actually choose their capacity, but since there is complete information this is equivalent to choosing the ratio.

Tolls are higher than with welfare maximisation as firms have market power, and this also means that the total number of users and total capacity are lower. Yet, as De Vany and Saving (1980) and Engel, Fisher and Galetovic (2004) show for a given capacity, as the number of firms increases, the equilibrium toll decreases and approaches the one under welfare maximisation under zero-profit.

2.3. Two-substages Nash

In the Two-substages Nash set-up of De Borger and Van Dender (2006), the capacity setting precedes the toll setting. In each substage, firms take the actions of the others in that substage as given. Firms have an incentive to set a lower capacity, as this lessens toll competition and increases Nash-equilibrium tolls: the lower total capacity is, the higher the toll a firm can set due to the higher congestion on the competitors’ roads. This alteration of the capacity rule means that firms set a higher volume/capacity ratio than is socially optimal. Zhang and Zhang (2006) study a monopolist airport’s choice of capacity and landing fare while carriers have market power, and find that it sets a lower ratio than socially optimal. Basso and Zhang (2007) extend this to two airports competing. Finally, Silva and Verhoef (2011) study up to 8 airlines competing Single-stage or Two-substages-Nash between a single origin and destination.

Using the formulas of De Borger and Van Dender (2006), we write the capacity rule

\[ k + \text{Strategic effect} = k - q^i \cdot \frac{\partial r^*}{\partial q^i} = -c^i \cdot q^i, \]  \hspace{1cm} (9)

where superscript * indicates that the toll is determined by the Nash toll-setting substage. Our modelling will assume that the outcome is symmetric in capacities. De Borger and Van Dender
(2006) find that, for their linear congestion technology and with very low marginal costs of capacity (0.25 or lower, where their base case cost is 1), an asymmetric equilibrium would result, which has slightly different characteristics. Still, even then, the volume/capacity ratios and tolls are higher than with Single-stage Nash.5

2.4. Stackelberg

In our Stackelberg game, firms set their capacities one after the other. Then the toll setting substage follows, in which tolls are set in a Nash fashion. The first firm to act is the leader. With its capacity, it influences the capacity setting of all other firms, as well as the outcome of the toll substage. By setting a higher capacity, the leader limits the capacities to be chosen by other firms, which raises its market power. Hence, the capacity rule is different than with welfare maximisation, and the leader’s ratio is lower than socially optimal. Still, this lower ratio also has a profit-reducing effect: given the actions of the others, it would be profit maximising to set the socially-optimal ratio. Optimal capacity (from the firm’s viewpoint) is found when, for a marginal capacity increase, the profit-increasing effect from the induced lower capacities of the competitors plus that of the lower user cost equals the profit-reducing effects from the stronger competition in the toll-setting substage and higher capacity cost.

If there are many firms acting sequentially, the second firm to act also has an incentive to set a ratio that is lower than socially optimal. However, its ratio will exceed that of the first firm, as it has fewer future capacity decisions to influence. The last firm to act has no capacities to influence. So it is only concerned with the toll setting substage. Just as in De Borger and Van Dender’s (2006) Two-substages Nash game, this firm sets a higher ratio in order to lessen the toll competition and raise the Nash-equilibrium tolls.

Since the firms set different volume/capacity ratios, their travel times are different. Since the generalised price must be the same on all roads, the first firm can ask the highest toll, because it has the shortest travel time. The last firm has the longest travel time and lowest toll.

Acemoglu, Bimpikis and Ozdaglar (2009) study a Stackelberg game with 2 firms that follows similar lines as ours, but they assume that demand is fixed (as long as the toll is not above the reservation utility) and that there is congestion. Their assumption of no congestion makes their model less applicable to markets with congestion such as roads, airports and telecommunication. In their setting, the second strategic concerns in the capacity setting of wanting to limit the toll competition does not occur, as in Nash equilibrium the tolls will always equal the reservation utility and thus cannot be affected. Moreover, total capacity always equals the fixed number of users. In their model, the only effect of being a leader is that the leader gets a larger market share.

5 We use the non-linear “Bureau of Public Roads” (BPR) function of travel time, and have only encountered symmetric outcomes in our numerical models, even for a marginal capacity cost as low as 0.05 where our base-case cost is 7. An advantage of the symmetric outcome is that in the analysis of De Borger and Van Dender (2006), it ensures that the response function of firm i’s capacity to firms j’s is negative; with asymmetry this need not be so. We assume that capacity costs are high enough to ensure downward-sloping response functions. In our numerical analyses, we have only encountered such downward-sloping functions, but our solution method does not assume this.
2.5. Sequential entry

Our last market structure follows Verhoef (2008) and is Sequential entry. This set-up is in between the Two-substages-Nash and Stackelberg set-ups. Again, there are separate substages for capacity and toll. When the first firm enters, it first sets its capacity and then toll, assuming that it is and will remain the only firm. Since there are no other players to influence, it is profit maximising to have the socially-optimal ratio. Then, a second firm enters, and optimises its capacity given that there is one other firm, and anticipating the toll-competition in the Nash substage. The capacity of the first firm is fixed, but it can change its toll. This is not as restrictive as it may seem. The first firm would like to decrease its capacity, but this is not directly possible and would certainly not result in it recuperating all capacity costs. Hence, the best it can do is to keep its current capacity. The second firm’s capacity influences the toll of the first firm, and this alters its capacity-setting rule, resulting in the second firm setting a higher ratio. Each further entry follows the same pattern as for the first two firms.

The Sequential entry set-up might seem inconsistent in that firms are forward-looking to the toll substage, but are continuously surprised when further entry occurs (i.e. they are myopic to the next capacity stage). But it also seems plausible that firms do not perfectly know what the future will bring and optimise given the current situation. Then an objection could be raised against the Nash and Stackelberg games, in which a firm has to know how many firms there will be. In reality, the market structure might be a mix of our Stackelberg and sequential-entry games: i.e. a firm does not know how many firms there will be, but has a prior belief about the likelihood of each outcome, and optimises given this belief. Therefore, it is useful to look at our two extremes: (1) Stackelberg, where firms know how many firms there will be, (2) Sequential entry, where firms are myopic to the possibility of further entry.

3. Numerical model

We use a numerical model to obtain insights into the relative performance of the schemes identified above. The calibration of our model follows Verhoef (2008). The model is simple, but it is calibrated to represent a realistic congested peak-hour highway. User cost follows the “Bureau of Public Roads” (BPR) function:

$$c^i[q^i/s^i] = \alpha \text{tf} \left(1 + 0.15 \left(\frac{q^i}{s^i}\right)^4\right)$$.

(10)

Free-flow travel time, $t_f$, is half an hour. Using a free-flow speed of 120 km/hour, this implies a trip length of 60 kilometres. The value of time, $\alpha$, is 7.5. Units of capacity are set so that a traffic lane corresponds to a capacity of $s^i=1500$. Capacity costs follow $C^i = k\cdot s^i$, where $k$ equals 7. Since our unit of time is an hour, $k$ is the hourly capacity cost. See Verhoef (2008, p. 476-477) for the derivation of $k=7$ from the total construction cost of €5 million per lane-km (or

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6 Zhang, Levinson and Zhu (2008) study a similar case with heterogeneous users and a large network: there is an existing public network, and firms decide to add a road based on the current situation, while on later dates they can alter the capacity and toll.
$8 million per lane-mile) for motorways in the Netherlands. This cost seems in line with estimates for the USA.\(^7\)

All roads have the same free-flow travel time. The initial capacity in the base equilibrium is \(s^0=1500\). Inverse demand follows

\[
D(Q) = A - B \cdot Q. \tag{11}
\]

The parameter \(A\) equals 61.27 and \(B\) 0.0117. In the base equilibrium, the resulting price elasticity is \(-0.5\). This calibration results in a very congested road in the base case, with a travel time that is 5.4 times the free-flow one. If the initial situation were less congested, the gain of private road supply and public policies would be lower.

3.1. Basic policies and Nash capacity competition

Table 1 describes the benchmark equilibria. It shows performance measures such as consumer surplus, welfare (the sum of consumer surplus and system profit), and relative efficiency, which is the welfare gain of a policy compared to the initial base equilibrium, relative to the First-best gain. It also gives the volume/capacity ratio averaged on the entire network, on the untolled part, and on the tolled part. In the base equilibrium, there is no tolling and capacity is 1500. In the First-best (FB) case, capacity is more than twice as large, and the toll equals the marginal congestion externality.

In the second-best (SB) case, the initial capacity remains untolled, but the new capacity has a welfare-maximising toll. Optimal capacity is higher than in the First-best case, but the volume/capacity ratio on the tolled part is the same. Due to the low initial capacity, the welfare gain of the second-best option is very close to the FB gain. With more initial capacity, the relative efficiency would be lower: the capacity expansion would be less important, while the detrimental effect of the larger untolled capacity would be larger. The SB set-up makes a large loss, and the government would have to finance this from other sources. This might be difficult in practice, and may lead to tax distortions elsewhere in the economy (which we ignore).

A single firm building and tolling an extra road is also welfare improving. In fact, private road supply is in our setting always welfare improving: the firm makes a profit; whereas the consumers cannot be worse off (since if users choose to use the private road, it cannot have a higher price than the untolled road). Again, the private road has the same volume/capacity ratio as the First-best network. Still, the price and toll are higher, and capacity is lower.

The final case in Table 1 is Second-best zero profit, where there is a fixed untolled road and a road for which the capacity and toll are set to maximise welfare under a self-financing constraint. This set-up circumvents the problem of the second-best case, where the government has to finance the substantial loss of the new road from other sources. This operator also sets the socially optimal ratio. We use this set-up as the benchmark for the private games, as it is the only one a private game could approach.

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\(^7\) Washington State Department of Transport (2005) reports 21 road construction projects from inside the state of Washington and 15 projects from outside the state. For outside the state, median cost is about $8 million per lane-mile while a third is above $10 million. For in the state, median cost is around $5 million while a quarter is above $10 million.
Table 1. Basic policies

<table>
<thead>
<tr>
<th></th>
<th>Base equilibrium</th>
<th>First-best</th>
<th>Second-best</th>
<th>Single Firm</th>
<th>Second-best zero profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity (S)</td>
<td>1500</td>
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<td>3734.0</td>
<td>2078.5</td>
<td>2708.7</td>
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<tr>
<td>Total demand (Q)</td>
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<td>4331.3</td>
<td>4782.7</td>
<td>4331.3</td>
<td>3927.9</td>
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<td>Toll</td>
<td>-</td>
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<td>0.31</td>
<td>10.29</td>
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<tr>
<td>Overall Q/S</td>
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<td>1.890</td>
<td>1.599</td>
</tr>
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<td>$q^0/s^0$ on untolled part</td>
<td>2.333</td>
<td>-</td>
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</tr>
<tr>
<td>$q^1/s^1$ on tolled part</td>
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<td>1.255</td>
<td>1.255</td>
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</tr>
<tr>
<td>Price</td>
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<td>20.42</td>
<td>-</td>
<td>5.46</td>
<td>15.43</td>
<td>10.72</td>
</tr>
<tr>
<td>$c^1$ on tolled part</td>
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<td>5.14</td>
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<tr>
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<td>Profit tolled part</td>
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<td>0</td>
<td>-14766</td>
<td>3417.32</td>
<td>0</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>71484</td>
<td>109468</td>
<td>133472</td>
<td>90029</td>
<td>109468</td>
</tr>
<tr>
<td>Welfare</td>
<td>60984</td>
<td>109468</td>
<td>108206</td>
<td>82946</td>
<td>98968</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0</td>
<td>1</td>
<td>0.974</td>
<td>0.453</td>
<td>0.783</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows the Single-stage Nash outcomes for varying number of firms. For ease of reference, we again include the Single firm outcome in the table. Remember that in all oligopolies, as well as with Second-best zero profit, there is an initial capacity that remains untolled. All firms set their tolls and capacities at the same time. Since the equilibrium is symmetric in that all firms have the same tolls and capacities, we give one set of results for any firm $i$. Because firms take the actions of the others as given, the best they can do is to set the socially-optimal volume/capacity ratio.

As the number of firms increases, the Single-stage Nash outcome approaches the Second-best zero profit case. With a single firm, the welfare gain is 58% of that under Second-best zero profit; with two firms, it is already 83%; and with 5 firms, it is 94% percent. This suggests that, in this context, a small number of firms may be enough to approach the best possible outcome.

Table 2. Single-stage Nash competition

<table>
<thead>
<tr>
<th>Final number of firms</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity (S)</td>
<td>2078.5</td>
<td>2411.4</td>
<td>2521.4</td>
<td>2572.7</td>
<td>2602.0</td>
</tr>
<tr>
<td>Total demand (Q)</td>
<td>3928.0</td>
<td>4150.5</td>
<td>4219.6</td>
<td>4250.9</td>
<td>4268.6</td>
</tr>
<tr>
<td>Average toll</td>
<td>10.29</td>
<td>7.69</td>
<td>6.88</td>
<td>6.52</td>
<td>6.31</td>
</tr>
<tr>
<td>Overall Q/S</td>
<td>1.890</td>
<td>1.721</td>
<td>1.673</td>
<td>1.652</td>
<td>1.640</td>
</tr>
<tr>
<td>$q^0/s^0$ on the untolled part</td>
<td>2.135</td>
<td>2.005</td>
<td>1.959</td>
<td>1.937</td>
<td>1.924</td>
</tr>
<tr>
<td>$q^1/s^1$ on each private road</td>
<td>1.255</td>
<td>1.255</td>
<td>1.255</td>
<td>1.255</td>
<td>1.255</td>
</tr>
<tr>
<td>Price</td>
<td>15.43</td>
<td>12.83</td>
<td>12.03</td>
<td>11.66</td>
<td>11.46</td>
</tr>
<tr>
<td>Profit firm $i$</td>
<td>3417.3</td>
<td>1206.7</td>
<td>557.2</td>
<td>315.9</td>
<td>202.6</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>90029</td>
<td>100518</td>
<td>103892</td>
<td>105440</td>
<td>106319</td>
</tr>
<tr>
<td>Welfare</td>
<td>82946</td>
<td>92432</td>
<td>95064</td>
<td>96204</td>
<td>96832</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0.453</td>
<td>0.649</td>
<td>0.703</td>
<td>0.726</td>
<td>0.739</td>
</tr>
<tr>
<td>Welfare gain relative to Second-best zero profit</td>
<td>0.578</td>
<td>0.828</td>
<td>0.897</td>
<td>0.927</td>
<td>0.944</td>
</tr>
</tbody>
</table>
3.2. Two-substages Nash Competition

Now we turn to the first of three set-ups where firms set their capacities strategically to influence the actions of the other firms. These strategic considerations change the capacity rule, which means that firms have a different volume/capacity ratio than is socially optimal. As Table 3 shows, with Two-substages Nash competition, firms have an incentive to set a lower capacity and a higher ratio, because this lessens the toll competition, thereby raising Nash-equilibrium tolls. However, this higher ratio comes at a cost for the firm: it raises its travel time and this lowers the toll users are willing to pay. The profit-maximising capacity is found where, at the margin, the opposing forces balance.

With two firms, the welfare gain of Two-substages Nash is much lower than with a single stage, as capacity is lower and tolls are higher. Yet, as the number of firms increases, the advantage for the firms from the two substages decreases. Our results indicate that this Two-substages Nash game approaches Single-stage Nash as the number of firms becomes large. This is also logical: if there are many firms, it is hard for a firm to influence the toll setting of others, as it only controls a tiny part of the total capacity. Hence, then the outcome is close to the Single-stage Nash outcome, where it is impossible to affect the toll setting of other firms.

Table 3. Two-substages Nash competition

<table>
<thead>
<tr>
<th>Final number of firms</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity (S)</td>
<td>2078.5</td>
<td>2292.3</td>
<td>2404.4</td>
<td>2470.2</td>
<td>2513.1</td>
</tr>
<tr>
<td>Total demand (Q)</td>
<td>3928.0</td>
<td>4087.1</td>
<td>4159.9</td>
<td>4200.0</td>
<td>4225.2</td>
</tr>
<tr>
<td>Average toll</td>
<td>10.29</td>
<td>8.27</td>
<td>7.44</td>
<td>6.99</td>
<td>6.72</td>
</tr>
<tr>
<td>Overall Q/S</td>
<td>1.890</td>
<td>1.966</td>
<td>1.815</td>
<td>1.747</td>
<td>1.710</td>
</tr>
<tr>
<td>q_i/s_i</td>
<td>2.135</td>
<td>2.044</td>
<td>1.999</td>
<td>1.972</td>
<td>1.955</td>
</tr>
<tr>
<td>q_i/s_0</td>
<td>1.255</td>
<td>1.288</td>
<td>1.285</td>
<td>1.280</td>
<td>1.277</td>
</tr>
<tr>
<td>Profit firm i</td>
<td>15.43</td>
<td>13.57</td>
<td>12.72</td>
<td>12.26</td>
<td>11.96</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>90029</td>
<td>97472</td>
<td>100971</td>
<td>102931</td>
<td>104170</td>
</tr>
<tr>
<td>Welfare</td>
<td>82946</td>
<td>89871</td>
<td>92787</td>
<td>94328</td>
<td>95266</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0.453</td>
<td>0.596</td>
<td>0.656</td>
<td>0.688</td>
<td>0.707</td>
</tr>
<tr>
<td>Welfare gain relative to Second-best zero profit</td>
<td>0.578</td>
<td>0.760</td>
<td>0.837</td>
<td>0.878</td>
<td>0.903</td>
</tr>
</tbody>
</table>

3.3. Sequential entry market structure

The sequential-entry market structure follows Verhoef (2008). Firms again have separate capacity and toll decisions. The difference is that now firms enter sequentially. First, firm 1 enters, and sets its capacity and then its toll, assuming that it will be the only firm. Next, a second firm enters and sets its profit-maximising capacity given that there is one other firm, while taking into account how this affects the toll-setting substage. So the first firm’s capacity is fixed, as this is a long-term decision; while its toll can be changed, as this is a short run decision. The entry pattern is the same for the third and further entrants. Firms are thus forward looking to the toll-setting substage, but myopic to the next entry (i.e. the next capacity stage). The difference with the Two-substages Nash is that now firms build their roads sequentially, which seems more realistic as historically not all roads have been built at the same time.
As Table 4 shows, even though all firms have the same cost structures and congestion technologies, they are ex-post asymmetric. This is due to the sequential decision making. The first firm sets a much higher capacity than it would under Nash competition, and this limits the capacities that the others will set. Yet, this sequential decision making need not be good for the firms, as becomes clear when comparing the profits in Fig. 1 (Sequential entry) with those in Table 3 (Two-substages Nash). For 4 or more firms, firm 1’s profit is lower with Sequential entry than with two-stage Nash. Firm 2 always has a lower profit with Sequential entry. For the up to 5 firms that we study, Sequential entry gives a higher welfare gain than Nash competition.

**Table 4. Results under Sequential entry**

<table>
<thead>
<tr>
<th>Final number of firms</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity ($S$)</td>
<td>2078.5</td>
<td>2399.1</td>
<td>2576.4</td>
<td>2670.3</td>
<td>2718.6</td>
</tr>
<tr>
<td>Total demand ($Q$)</td>
<td>3928.0</td>
<td>4138.4</td>
<td>4237.3</td>
<td>4285.0</td>
<td>4308.4</td>
</tr>
<tr>
<td>Average toll</td>
<td>10.29</td>
<td>7.86</td>
<td>6.80</td>
<td>6.30</td>
<td>6.05</td>
</tr>
<tr>
<td>Overall $Q/S$</td>
<td>1.890</td>
<td>1.725</td>
<td>1.645</td>
<td>1.605</td>
<td>1.585</td>
</tr>
<tr>
<td>$q_0^0/s_0^0$</td>
<td>2.135</td>
<td>2.012</td>
<td>1.946</td>
<td>1.912</td>
<td>1.894</td>
</tr>
<tr>
<td>Capacity firm 1 ($s^1$)</td>
<td>578.5</td>
<td>578.5</td>
<td>578.5</td>
<td>578.5</td>
<td>578.5</td>
</tr>
<tr>
<td>Capacity firm 2 ($s^2$)</td>
<td>-</td>
<td>320.5</td>
<td>320.5</td>
<td>320.5</td>
<td>320.5</td>
</tr>
<tr>
<td>Capacity firm 3 ($s^3$)</td>
<td>-</td>
<td>-</td>
<td>177.4</td>
<td>177.4</td>
<td>177.4</td>
</tr>
<tr>
<td>Capacity firm 4 ($s^4$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>93.8</td>
<td>93.8</td>
</tr>
<tr>
<td>Capacity firm 5 ($s^5$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>48.3</td>
</tr>
<tr>
<td>Price</td>
<td>15.43</td>
<td>12.98</td>
<td>11.82</td>
<td>11.26</td>
<td>10.99</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>90029</td>
<td>99931</td>
<td>104767</td>
<td>107138</td>
<td>108308</td>
</tr>
<tr>
<td>Welfare</td>
<td>82946</td>
<td>91939</td>
<td>95687</td>
<td>97365</td>
<td>98153</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0.453</td>
<td>0.638</td>
<td>0.716</td>
<td>0.750</td>
<td>0.767</td>
</tr>
<tr>
<td>Welfare gain relative to Second-best zero profit</td>
<td>0.578</td>
<td>0.814</td>
<td>0.910</td>
<td>0.953</td>
<td>0.973</td>
</tr>
</tbody>
</table>

![Fig. 1. Firm profit by the final number of firms under Sequential entry](image)

As the final number of firms increases, total capacity increases and tolls decrease (see Fig. 2), leading to lower profits. Firm 1 always has the largest profit due to its largest size. The later a firm entered, the lower its profit is. The sequential-entry market structure does not actually reach the Second-best zero profit case when the number of firms goes to infinity. With 5 firms, total capacity is already higher, and the entries of the sixth and seventh firms only increase capacity further (these cases are not shown, but they were calculated). It is perhaps surprising
that such a capacity level can be profitable. The reason is that, with five firms, a firm still has market power, and can add a mark-up to the toll (see also Fig. 2); whereas under Second-best zero profit, the toll equals the congestion externality and the mark-up is zero. Still, the welfare loss from this is limited. Two firms entering sequentially gives a consumer surplus that is 9% lower and welfare gain that is 19% lower than under Second-best zero profit; for five firms these figures are, respectively, 1% and 3%.

An intriguing result with Sequential entry is the development of the volume/capacity ratios in Fig 3. When firm 1 enters, it sets the socially-optimal ratio, since there are no other players to influence. When firm 2 enters, it sets a higher ratio, as this increases Nash-equilibrium tolls, thereby increasing its profit. Since the first capacity is fixed but the new entry attracts users away, the first firm’s ratio decreases and is now lower than socially optimal. The average ratio on the private roads also decreases, because firm 1 is larger. For later entries a similar pattern holds: the entrant sets a ratio that is higher than socially optimal to limit the toll competition, and the ratios of the incumbents and the overall ratio decrease.

3.4. Stackelberg capacity competition

Our last market structure extends the previous one by making firms forward looking in their capacity choices: they recognise that their capacity influences the capacity setting of all following firms as well as the Nash toll-setting substage. The difference with the previous
setting is that now firms know how many firms there will eventually be, whereas before they assumed that they would be the last entrant. It is important to emphasise that for each number of firms the table and figures give the results after the final stage. Unlike with sequential-entry, the various number of firms cannot be viewed as intermediate stages in the same dynamic process.

Fig. 4 and Table 5 show the results. With two firms, the leader sets a higher capacity and thus a lower ratio than the follower, which reflects that the leader has more market power and a shorter travel time, allowing it to ask a higher toll. Still, the leader’s capacity is below the one with Sequential entry, as this lower capacity lessens toll competition, which raises profit even though it also raises the capacity of firm 2. The leader’s capacity is well above the single- or Two-substages-Nash level. For three or more entrants, the results follow the same lines.

**Table 5.** Results under Stackelberg capacity competition

<table>
<thead>
<tr>
<th>Final number of firms</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity ($S$)</td>
<td>2078.5</td>
<td>2397.6</td>
<td>2564.2</td>
<td>2647.2</td>
<td>2686.6</td>
</tr>
<tr>
<td>Total demand ($Q$)</td>
<td>3928.0</td>
<td>4137.8</td>
<td>4233.6</td>
<td>4279.0</td>
<td>4301.2</td>
</tr>
<tr>
<td>Average toll</td>
<td>10.29</td>
<td>7.87</td>
<td>6.82</td>
<td>6.32</td>
<td>6.06</td>
</tr>
<tr>
<td>Overall $Q/S$</td>
<td>1.890</td>
<td>1.726</td>
<td>1.651</td>
<td>1.616</td>
<td>1.601</td>
</tr>
<tr>
<td>$q^0/s^0$</td>
<td>2.135</td>
<td>2.013</td>
<td>1.949</td>
<td>1.916</td>
<td>1.890</td>
</tr>
<tr>
<td>Capacity firm 1 ($s^1$)</td>
<td>578.5</td>
<td>576.2</td>
<td>543.4</td>
<td>489.7</td>
<td>428.3</td>
</tr>
<tr>
<td>Capacity firm 2 ($s^2$)</td>
<td>-</td>
<td>321.5</td>
<td>336.5</td>
<td>350.7</td>
<td>345.8</td>
</tr>
<tr>
<td>Capacity firm 3 ($s^3$)</td>
<td>-</td>
<td>-</td>
<td>184.3</td>
<td>201.0</td>
<td>226.5</td>
</tr>
<tr>
<td>Capacity firm 4 ($s^4$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>105.8</td>
<td>122.</td>
</tr>
<tr>
<td>Capacity firm 5 ($s^5$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>63.2</td>
</tr>
<tr>
<td>Price</td>
<td>15.43</td>
<td>12.98</td>
<td>11.86</td>
<td>11.33</td>
<td>11.08</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>90029</td>
<td>99902</td>
<td>104580</td>
<td>106837</td>
<td>107949</td>
</tr>
<tr>
<td>Welfare</td>
<td>82946</td>
<td>91916</td>
<td>95558</td>
<td>97177</td>
<td>97943</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0.453</td>
<td>0.638</td>
<td>0.713</td>
<td>0.746</td>
<td>0.762</td>
</tr>
<tr>
<td>Welfare gain relative to Second-best zero profit</td>
<td>0.578</td>
<td>0.814</td>
<td>0.910</td>
<td>0.953</td>
<td>0.973</td>
</tr>
</tbody>
</table>

For an end equilibrium with up to 4 firms, the volume/capacity ratio of firm 1 decreases with the number of firms. Yet, with 5 firms, it is higher than with 4 firms. This suggests that, as the number of firms increases even further than 5, the ratios of all firms may approach the socially-optimal ratio. With more firms, it is more difficult to influence the capacity and toll setting of others, and trying this becomes less profitable. Conversely, the profit loss from setting a lower ratio remains, in that the increase in capacity cost is larger than the toll revenue gain due to the lower travel time; while for a higher ratio, the capacity cost reduction is offset by a larger loss in revenue. Only when it is possible to influence the actions of the others is it profitable to set a different ratio, but with many firms, the strategic effect is small. Certainly, as Figs. 5 and 6...

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8 Because we are unable to find an analytical best-response function of firm i’s capacity on j’s, we numerically approximate the best-response functions. To calculate the capacity of the last firm, one only needs how the outcome of the Nash-toll competition depends on its capacity. For the second-to-last firm, one also needs how the last firm’s capacity depends on the second-to-last firm’s. For the third-to-last firm one also needs how the last and second-to-last respond to its actions. And so on for each further firm. Hence, the complexity of the problem increases very rapidly with the number of firms.
indicate, the tolls and profits seem to approach their values in the benchmark case of Second-best zero profit. Due to computational complexity that rapidly increases with the number of firms, we were unable to verify this for 6 or more firms.

**Fig. 4.** Volume capacity ratio on each road under Stackelberg capacity competition

**Fig. 5.** The toll of each firm by the final number of firms under Stackelberg competition

**Fig. 6.** Firm profit by the final number of firms under Stackelberg competition
3.5. Comparison of the oligopolistic market structures

Fig. 7 compares the average volume/capacity ratios in the different oligopolistic settings. It also shows the ratio of a public operator as a benchmark. Single-stage Nash results in constant private ratios that are socially optimal. When the capacity and toll competitions are separate substages, firms set a higher ratio to lessen the later toll competition. Still, with Nash competition this ratio appears to approach the level with welfare maximisation under zero profit as the number of firms increases. Conversely, in the Sequential entry game where firms set their capacities one after the other, the average ratio is lower than socially optimal, and further entry only decreases the ratio further. For Stackelberg competition, the average ratio seems to level off at five firms.

Sequential entry never reaches the outcome under Second-best zero profit. As Fig. 8 also shows, in our numerical model, the capacity level with 5 firms is already above with Second-best zero profit, and further entry only increases capacity.

Figs. 8 and 9 compare the capacities and relative efficiencies in the different market structures. All set-ups lead to substantial welfare gains that, even for 2 firms, are relatively close to the zero-best zero profit outcome. Only with a Single firm is the relative efficiency much lower, at 0.453. Two-substages Nash attains of all oligopoles the lowest gain, as firms build less capacity and have higher tolls.
4. Discussion

The Stackelberg and Sequential entry games have very similar results. A weakness of the Stackelberg model is that firms have to know with certainty how many firms there eventually will be. Conversely, with Sequential entry, each firm assumes that it is the last entrant, and every firm is “surprised” when a further entry occurs. Both models seem useful benchmarks, and it seems likely that in reality the outcome would be somewhere in between these two games. Given the closeness of the results, we expect that such a more realistic model would give similar outcomes to the cases considered here.

It is important to perform sensitivity analyses to important parameters. We have tested various key parameters, but will focus on the size of initial capacity. More initial capacity lowers the gain of the First-best policy, as there is less to gain from the capacity expansion. For the second-best, single-firm and second-best zero-profit cases, the gain and relative efficiency decrease with the size of the initial capacity: capacity expansion is less important and there is more initial capacity that remains untolled (see also Verhoef, 2007). The gains of the oligopolistic settings also decrease with the size of the initial capacity; but relative to Second-best zero profit they fare better, as the larger untolled capacity limits the market power.

In our model, entry by a firm is always welfare improving. This is unrealistic if there are fixed costs to building a road or a minimum road size. Firms then would enter up to the point that it is profitable. If there are fixed costs of starting a road, a large number of firms would even harm welfare. Instead the socially optimal number of firms then is where the welfare gain of an extra firm equals the fixed cost. With a minimum road size, the optimal number of firms is where the addition of an extra discrete private capacity would lower welfare.

The reader might wonder whether our setting with many firms competing in parallel is realistic, as it is rare to have many toll roads going from the same origin to the same destination. We emphasize that we consider up to 5 firms primarily to learn more on the asymptotic behaviour of the various market forms. Still, our set-ups can also be applied for different congestible markets such as telecommunication, railways, airports, and airlines: for example,

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9 The effects of other such aspects as price elasticity and value of time turned out to be as one would expect. For instance, more price sensitive demand makes private provision more beneficial, as it limits market power.
Silva and Verhoef (2011) study price and capacity setting by up to 8 airlines. Also in different network structures, such as serial markets or competing destinations, strategic choices might affect the quality and price setting; making these alternative network structures interesting themes for follow-up research. Complementary analyses using larger, more realistic, networks may also be needed to give further insights that would be relevant for applied policy: notably, for the design of auctions for the right to build and operate a private infrastructure. Observing how computationally intensive the Stackelberg game is compared with Sequential entry and how similar their results are, it might be better to use the latter in larger networks, as especially in larger networks the computational burden is important.

We ignore heterogeneity in the preference of users, but introducing this would be an interesting extension of our model. Edelson (1971) and Mills (1981) show that with heterogeneous users, the monopolist may charge a toll that is in fact lower than socially optimal. Moreover, under heterogeneity, even Nash-competing firms generally offer different qualities, as this product differentiation raises profits. Luski (1976) and Calcott and Yao (2005) show this when firms compete only on tolls, and Reitman (1991) shows this when firms compete Single-stage Nash on tolls and capacities. As Winston and Yan (2011) and Verhoef and Small (2004) argue, such product differentiation by firms will generally make users better off, as they can self-select to the road that suits them the best. Therefore, the welfare gain of private supply with multiple parallel roads would generally be higher with heterogeneity.

We assume that the capacity and operating costs are the same for the government and private firms. Naturally, if private supply is much more efficient, it might have a higher welfare than (second-best) supply by the government. However, even then the market power lowers welfare; and, if firms have strategic concerns, they set a different travel time than is socially optimal given their capacity cost. Hence, also then, there is scope for regulation, and this seems an interesting topic for research with possibly important implications for policy.

Such regulation could take the form of auctions for the right to build a road, where firms for example, compete on bid (i.e. transfer to the government), maximum toll, minimum number of users, or road capacity. Consider a perfectly-competitive auction on capacities for two parallel roads (where a firm cannot have both). Firms bid up their capacities to the point where profit is zero. Under Nash competition, since the firms have market power and thus add a mark-up to the toll, this can only happen when the volume/capacity ratio (and thus travel time) is lower than socially optimal. Such regulation of private firms seems a promising topic for future research.

5. Conclusion

This paper considered capacity, price, and service-quality setting in oligopolistic markets for congestible services applied to the case of road transport. Assuming that capacity is perfectly divisible, previous studies show that firms competing in parallel set a service quality (i.e. travel time) that is socially optimal if they take the actions of the others as given in a Nash fashion.

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In addition, if the number of toll roads keeps increasing, which seems likely, the chance that there are multiple roads going roughly in the same direction increases. Or alternatively, as a referee pointed out, there might be multiple firms operating on the same multi-lane highway: for instance, that next to an express-lane a second express lane arises. Difficulties with such a set-up include how to deal with common costs such as lighting and safety-barriers.
We find that this Single-stage Nash-competition assumption is crucial. If firms can influence the decisions of others with their capacity, this changes their capacity-setting rule, and they generally set a different travel time than the socially optimal one.

In our Stackelberg market structure, firms first set their capacities one after another and then set their tolls in a Nash fashion. Firms have two strategic considerations: (1) they want to limit the capacities of firms that follow by setting a higher capacity, and (2) they want to limit the toll competition by setting a lower capacity. The first firms to act have many capacities to influence, and hence set a higher capacity, and thus a lower travel time, than they otherwise would. The last firms have few if any capacities to influence, and set a higher travel time.

Strategic setting of a lower capacity to limit toll competition is harmful for welfare as it lowers capacities and increases tolls. Stackelberg setting of higher capacities to limit competitors’ capacities can be good or bad for welfare: because Stackelberg competition can also lead to stronger toll competition. Concluding, Stackelberg competition leads to the average private travel time being too low from a societal point of view; but it depends whether welfare is lower than under Nash competition as it can also lead to stronger toll competition.

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References


Appendix A

This appendix supports our overview of the literature in a form that facilitates comparison. In Table A.1’s toll-rule column, \( MEC \) stands for the marginal external cost, and it is what the toll should be following the First-best (FB) rule. All firms add a mark-up, but the exact form depends on the situation, on the number of competitors, and type of competitors. In FB optimum, the capacity is set so that for a marginal expansion the capacity cost (here \( MC_{\text{cap}} \) as some authors use non-constant marginal cost, and in the text \( k \) as we use a fixed level) equals the reduction in user cost \((-q c'_i)\) it achieves. If there is only 1 firm or when firms compete Single-stage Nash, a firm uses the same capacity rule as in the FB optimum; only when a firm can influence the actions of other firms does it use another rule (see also the introduction).

<table>
<thead>
<tr>
<th>Source</th>
<th>Context</th>
<th>Toll</th>
<th>Capacity rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>(see section 2.1)</td>
<td>First-best optimum</td>
<td>MEC</td>
<td>( MC_{\text{cap}} = -q c'_i )</td>
</tr>
<tr>
<td>De Borger and Van Dender (2006)</td>
<td>2 parallel roads competing two-stages Nash</td>
<td>MEC+mark-up</td>
<td>( MC_{\text{cap}} = -q c'_i + \text{strategic effect on toll competition} )</td>
</tr>
<tr>
<td>Buchanan (1956)</td>
<td>Single road</td>
<td>MEC+mark-up</td>
<td>Fixed capacity</td>
</tr>
<tr>
<td>Mohring (1985)</td>
<td>Single road</td>
<td>MEC+mark-up</td>
<td>Fixed capacity</td>
</tr>
<tr>
<td>Verhoef (2007)</td>
<td>Single firm + possible parallel or serial untolled road</td>
<td>MEC+mark-up</td>
<td>( MC_{\text{cap}} = -q c'_i )</td>
</tr>
<tr>
<td>Winston and Yan (2011)</td>
<td>1 or 2 parallel firms with heterogeneous users</td>
<td>MEC+mark-up</td>
<td>Fixed capacity</td>
</tr>
<tr>
<td>Wu et al. (2011)</td>
<td>Firms in general network competing Single-stage Nash</td>
<td>MEC+mark-up</td>
<td>( MC_{\text{cap}} = -q c'_i )</td>
</tr>
<tr>
<td>Xiao et al. (2007)</td>
<td>Parallel roads competing Single-stage Nash</td>
<td>MEC+mark-up</td>
<td>( MC_{\text{cap}} = -q c'_i )</td>
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