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# Market power of railway operators under different vertical structures ☆

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ABSTRACT

This paper theoretically and quantitatively investigates the effects of structural reforms – separation between infrastructure operations and train operations and the introduction of competition – on the degree of market power downstream, as measured by the Lerner index, by explicitly considering economies of scale at the infrastructure level and regulated access fees. We find that vertical separation reduces the degree of market power when there is a monopoly downstream. Besides, under vertical separation, the Lerner index under duopoly downstream exceeds that under monopoly when economies of scale are large enough. This follows from incomplete pass-through of access fees to prices. Our quantitative analysis indicates that, compared to separation, the Lerner index is higher and consumer surplus and social welfare are also higher in the case of a vertically integrated monopoly. With competition downstream, an integrated structure yields decreases in the integrated operator's degree of market power and modest gains in terms of consumer surplus and social welfare for low degrees of product differentiation compared to separation. Larger economies of scale result in lower rail prices and access fees, which enhance consumer surplus and industry profits although the Lerner indices go up.

## 1. Introduction

The organization of a vertically linked industry which is a natural monopoly upstream and potentially competitive downstream is a much-debated question. In railways, infrastructure provision is naturally monopolistic and characterized by indivisibilities and economies of scale while competition in the supply of rail services has been gradually promoted. Infrastructure charges, that may respond to different principles, represent a significant part of operators' costs. To some extent, charges will eventually be translated to prices and how they are set is central for an effective competition downstream. This paper theoretically and quantitatively investigates the effects of structural reforms – separation between infrastructure and services and the introduction of competition – on the degree of market power downstream, as measured by the Lerner index, by explicitly considering economies of scale at the infrastructure level.[1]

How to introduce competition in regulated network industries, such as electricity, telecommunications or railways is a complex matter [3]. Regulators and policymakers are concerned about access to the network, the rules to fix access charges, the presence of a vertically integrated incumbent and the exercise of market power (see [4,15] for excellent reviews on the theoretical literature on regulation). To be sure, the presence of economies of scale in infrastructure provision and the integrated or separated structure between infrastructure and rail operations, not only affect the efficient behavior of the industry (as studied in the literature), but also the degree of market power and the competitive performance of the market.

Many economists and policy-makers are raising concerns on market concentration and the sharp rise in firm markups since 1980 which have accelerated its pace since 2010 (see [5,12]). Markups arise when sellers exercise market power, that is, by firms raising prices relative to what firms would charge in a competitive market. The exercise of market power is harmful in different ways as for instance by inducing allocative efficiency losses, by fostering wasteful rent-seeking behavior and by slowing productivity improvements and innovation. In view of

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[1] The existence of substantial fixed costs (particularly, those associated with infrastructures) has traditionally led economists to assume the presence of important economies of scale in this industry (see [9,13]).

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the above, it is paramount to find the reasons that explain why price-marginal costs differences increase. It can be because prices increase, or because firms are able to operate at lower costs, or a combination of both. We propose an explanation for Lerner indices changes in the railway industry that hinges on the exploitation of scale economies enjoyed by infrastructure providers.

The old management system in railways was one of complete integration of activities into a single public firm, both at the vertical dimension level between infrastructure and rail operations and at the horizontal level between all the different rail services. In the last decades, most European countries, in the light of the various European Railway Packages have reorganized the rail sector by separating infrastructure from operations and introducing competition, on equal grounds for incumbents and entrants, in the supply of rail services (see [19,23,26], for reviews). While some European countries have kept an integrated rail structure (such as Ireland, Hungary, Lithuania, Luxembourg or Russia), most European countries have opted for a more disintegrated structure (United Kingdom, Sweden, Netherlands, Spain, Finland, Belgium, etc.). However, a few countries (such as Germany and recently France) keep a holding model where the infrastructure manager is in charge of the infrastructure within a whole rail group. Regarding the introduction of competition, Sweden, Germany and the UK have opted for franchising while Italy, the Czech Republic and Spain have promoted on-track competition (for some important routes, although the former countries also have on-track in some lines) in high-speed rail passenger services. Competition among several operators in freight transport has been fairly common. The idea of the infrastructure as a natural monopoly, separated from non-natural monopoly components, was supposed to be applied in the European countries as an effective way to promote competition [6,19,26]. This was the economic rationale to justify the separation between rail infrastructure and operations. The low proportion of fixed costs in the supply of the rail operations would allow the introduction of competition, either by direct entry in the commercial markets or by franchising systems in public service obligations.

The debate about the results of these reestructuring measures is yet alive, but there is a consensus that competition has promoted a more efficient and productive behavior of the industry. However, the literature has provided mixed and far from conclusive effects on the effectiveness and productivity of this unbundling procedure ( see [11,20,23]). The recent contribution by [24] formally studies key cost factors that determine the choice of vertical structure; separation is preferable for smaller train density, and for larger technological effects of scope economies between operation and infrastructure activities. Finally, according to the European Commission, rail access charges are fundamental for the success of restructuring measures in railways since they are applied by the infrastructure manager to operators. The implications of infrastructure access fee pricing on the optimality and the financial independence of the industry have led regulators to employ different mechanisms, which combine the incentives to fix an efficient system with a variable degree of cost recovery [25,26]. Systems trying to recover significant fixed costs have been implemented as two-tariff systems, Ramsey-pricing, average cost pricing and cross subsidies. In any case, in Europe most of the countries follow a system based on an “average cost pricing” regarding the criteria to set the track charges, but these costs exclude an important share of the fixed upfront costs, which are only partially amortized [6,19,27,29]. We shall, for the sake of the exposition, consider average cost regulation. Some contributions exist that have explored the degree of market power in transport, such as [17,21] for rail, [18,32] for US airlines and the Chinese airline industry, respectively; [33] study the impact of high-speed rail on concentration and the Lerner index in China’s airline market.

It is well known that with constant/increasing returns and a one-tier industry, more competition results in lower values of Lerner indices. [31] discusses the pros and cons of vertical separation in a vertically linked industry. He assumes economies of scale downstream and a setting where the number of firms is endogenously determined. Interestingly, Vickers shows that integration need not be desirable in welfare terms. [30] also studies the effects of entry downstream where the wholesale price (here access fee) is unregulated and demand is convex; entry may decrease total output and increase the price. In contrast with these papers, we consider increasing returns upstream and also regulated access fees that are equal to average cost. Our analysis draws on the relevance of the size of economies of scale upstream in establishing a non-monotonicity result between more competition and the degree of market power.

In view of the above, in the first part of our paper we shall develop a theoretical setting that considers: i) market structure characteristics, ii) economies of scale at the infrastructure level, and iii) access fees that are regulated, to calculate Lerner indexes. The analysis and results depend on the size of economies of scale, the degree of product differentiation among operators and to what extent changes in access fees, which depend on the particular vertical structure, pass through to prices. Specifically, we find that vertical separation reduces the degree of market power when there is a monopoly downstream. However, under vertical separation in case of a duopoly downstream changes in the degree of market power depend on the size of economies of scale. Thus, we find that the Lerner index under duopoly downstream exceeds that under monopoly when economies of scale are large enough. The key to such unexpected result is that the lower access fees under duopoly are passed through to prices to a lower extent; this means that competition may produce increased market power for sizeable economies of scale. In the second part, we provide an empirical application using data from the Spanish operator. The model is calibrated using the available data on elasticities, prices, traffic levels, and operating costs. We also estimate an infrastructure cost function using data from a sample of European infrastructure providers. The estimate confirms the existence of economies of scale in infrastructure provision. Our quantitative analysis in the case of a monopoly rail operator suggests that the Lerner index is higher under an integrated structure although consumer surplus and social welfare are also higher compared to separation. With competition downstream, an integrated structure yields decreases in the integrated operator’s degree of market power and modest gains in terms of consumer surplus and social welfare for low degrees of product differentiation. It is also found that, when economies of scale become more relevant, rail prices and access fees fall, which enhance consumer surplus and industry profits yet the Lerner indices go up. Finally, entrants very often tend to offers a kind of a low-cost service. We find that the smaller the service quality difference between the incumbent and the entrant operators, the lower the degree of market power and the better for consumers and society.

The next section presents the model. Two subsections offer the characterization of the downstream monopoly and duopoly cases; the main results are provided. The empirical application is given in Section 3, before closing with some concluding remarks and managerial implications.

## 2. The model

Consider a transport market between two cities that is operated by rail transport. The infrastructure monopolist enjoys economies of scale and sets the access fee, while the rail operators set the price paid by users to maximize profits and enjoy constant returns to scale. We will consider the following market configurations in the case of a successive monopoly: i) there is vertical separation and the infrastructure provider has its access fee regulated to equal the average cost of providing the service; and ii) there is vertical integration in the market. The case of vertical separation where both firms set prices to maximize profits is also reported. Next we consider the effect of downstream entry and solve for two possible situations. Either there is vertical separation or there is vertical integration between the infrastructure provider and one of the railway operators. In both cases the infrastructure manager set the access fee to equal average cost of providing the service. We characterize the equilibrium outcomes and compare the Lerner indices resulting from the aforementioned vertical market configurations.

The utility functions of the representative passenger under monopoly and duopoly are as follows (see [14]):

$$U^m = \alpha q - \frac{\beta}{2}q^2, \tag{1}$$

$$U^d = \alpha(q_1 + q_2) - \frac{\beta}{2}(q_1^2 + q_2^2) - \gamma q_1 q_2, \tag{2}$$

where $q$ denotes the number of passengers traveling in the monopoly case and $q_l$, with $l = 1, 2$ denotes the number of passengers traveling with operator $l$ in the duopoly case. Maximization of $U^m$ subject to the budget constraint yields the inverse demand function, $p = \alpha - \beta q$, where $p$ denotes the price for traveling when there is one operator, $\alpha > 0$ denotes the maximum willingness to pay by the representative passenger in any of the cases analyzed and $\beta$ is the rate at which marginal utility of a given output decreases when the representative passenger increases consumption of such good, or the effect on price of an increase in demand by one unit. Then we have the following:

i) downstream monopoly demand:

$$q(p) = a - bp \tag{3}$$

where $a = \frac{\alpha}{\beta}$ and $b = \frac{1}{\beta}$.
In case there are two operators, maximization of $U^d$ subject to the budget constraint yields a system of inverse demand functions, i.e. $p_1 = \alpha - \beta q_1 - \gamma q_2$ and $p_2 = \alpha - \beta q_2 - \gamma q_1$, where $p_l$ denotes the price for traveling using operator $l$. Note that $\beta$ is, as before, the own-effect on price, how much $p_l$ decreases by increasing $q_l$ by one unit with $l = 1, 2$; while $\gamma$ denotes the cross-effect on price or how much $p_1$ ($q_2$) decreases by increasing $q_2$ ($p_1$) by one unit. Finally, the services provided by operators are substitutes and own-effects are larger than cross effects, i.e. $\beta > \gamma > 0$. The degree of product differentiation is expressed by $\frac{\gamma^2}{\beta^2}$, ranging from zero for independent products to one for perfect substitutes. Inverting that system, we have the following demand:

ii) downstream duopoly market demand system:

$$q_1(p_1, p_2) = A - Bp_1 + dp_2 \tag{4}$$

$$q_2(p_1, p_2) = A - Bp_2 + dp_1 \tag{5}$$

In order to undertake the comparisons between the Lerner indices in monopoly and duopoly, we use $\tau$ as a single parameter that measures how aggregated market size and the degree of product differentiation are related. After defining $\tau$ as $\tau = \frac{\beta}{\beta+\gamma}$, it follows that $A = \tau a$; $B = (\frac{\tau^2}{2\tau-1})b$, $d = (\frac{\tau(1-\tau)}{2\tau-1})b$. If both services are not competing, $\gamma = 0$ (or $\tau = 1$), the competition effect is zero while the market expansion effect is one ($A = a$), $B = b$ and $d = 0$. In the limit case of services considered as identical $\beta = \gamma$ (or $\tau = 1/2$), the competition effect is maximal ($B$ and $d$ are defined as equal to $b$), while the market expansion effect is naught ($A = \frac{a}{2}$). Therefore, we assume that $\tau \in (1/2, 1]$.

**Profits.**

*Infrastructure provider.*

The infrastructure provider has the following profit function, which identifies the revenues obtained by offering the service to the railway operators and infrastructure costs.

$$\Pi^{im} = wQ - (cQ - kQ^2) \tag{6}$$

where $w$ denotes the access fee per passenger paid by the railway operators, $Q$ is either $q$ if there is just one railway operator or $q_1 + q_2$ if there are two. Also, $c > 0$ is the constant part of the marginal cost of providing the service, while $k > 0$ measures the size of economies of scale in such provision.[2]

*Railway operators.*

Regarding railway operators they have the following profit functions:

i) downstream monopoly:

$$\Pi^{op} = (p - w - v)q(p) \tag{7}$$

ii) downstream duopoly:

$$\Pi_1^{op} = (p_1 - w - v)q_1(p_1, p_2) \tag{8}$$

$$\Pi_2^{op} = (p_2 - w - v)q_2(p_1, p_2) \tag{9}$$

where $v > 0$ denotes marginal costs apart from the access fee paid to the infrastructure provider.

### 2.1. The downstream monopoly case

In this subsection, we focus on the case of a monopoly operator and we compute the market equilibrium under two different situations where access fees are set to equal average costs. We distinguish whether the operator is integrated with the infrastructure provider. In particular, the i) Vertically separated monopoly and the ii) Vertically integrated monopoly scenarios.

*i) Vertically separated monopoly.*

The model is a two stage game, where in the first stage the infrastructure manager sets the access fee per passenger to equal the average cost of providing the service. In the second stage, the monopoly operator chooses the profit maximizing price. The game is solved in the standard backwards way. Given that, the monopolist operator sets the profit maximizing price, which is given by,

$$p(w) = \frac{a + b(w + v)}{2b}. \tag{10}$$

The regulated access fee is equal to

$$w_s^m = c - \frac{k(a - b(c + v))}{(2 - bk)}, \tag{11}$$

where subscript $s$ denotes separation and upperscript $m$ monopoly. Substitution of (11) in (10) yields the equilibrium price,

$$p_s^m = \frac{a + b(c + v) - abk}{b(2 - bk)}. \tag{12}$$

Note that both, $w_s^m$ and $p_s^m$ are decreasing in $k$ and that the magnitude of the decrease in $w$ is twice that of $p$ in absolute terms. Equilibrium output, operator margin and Lerner index at equilibrium are, respectively:

$$q_s^m = \frac{a - b(c + v)}{(2 - bk)} \tag{13}$$

[2] This functional form is very convenient to account for economies of scale. It has been widely employed since the pioneering papers by [7,8]. It should be noted though that the literature usually refers to economies of traffic density to capture that the average cost declines with the increasing traffic level, but not with the expanding of the rail infrastructure itself. We shall use economies of scale for the sake of the analysis.

$$p_s^m - w_s^m - v = \frac{a - b(c+v)}{b(2-bk)} \tag{14}$$

$$L_s^m = \frac{a - b(c+v)}{a + b(c+v) - abk} \tag{15}$$

*ii) Vertically integrated monopoly.*

In this case, the infrastructure provider and the railway operator maximize joint profits, as a result of which the equilibrium price is independent of the access fee. Therefore, the choice of $w$ is immaterial. The integrated firm decides on prices taking into account the existence of scale economies and results in the following expression where subscript $i$ denotes integration,

$$p_i^m = \frac{a + b(c+v) - 2abk}{2b(1-bk)}. \tag{16}$$

To conduct sensible comparisons with the other industry situations, the access fee that would equal average costs of providing the infrastructure is considered, that is,

$$w_i^m = c - \frac{k(a - b(c+v))}{2(1-bk)}. \tag{17}$$

Equilibrium output, operator margin and Lerner index at equilibrium are, respectively: .[3]

$$q_i^m = \frac{a - b(c+v)}{2(1-bk)} \tag{18}$$

$$p_i^m - c - v + 2kq_i = \frac{a - b(c+v)}{2b(1-bk)} \tag{19}$$

$$L_i^m = \frac{a - b(c+v)}{a + b(c+v) - 2abk} \tag{20}$$

Notice that now the operator margin is computed using the actual marginal cost of providing the whole service (i.e. $c - 2kq_i + v$). The next Proposition can be stated. All proofs are available on request.[4]

**Proposition 1.** The following rankings arise:

i) $L^m < L_s^m < L_i^m$
ii) $p_i^m < p_s^m < p^m$
iii) $w_i^m < w_s^m < w^m$

The separation of infrastructure from operator activities results in a higher access fee. A part of such variation is passed through to the price paid by users. In fact, there is incomplete pass-through, this meaning that the price increase is smaller than the increase in the access fee. Therefore, separation leads to a lower value of the Lerner index.

If there were a gain in the size of economies of scale, then we would expect a fall both in the access fee and price - as noted above. Because of the above mentioned incomplete pass-through rate, we would observe that the market power of operators goes up, whether under integration or separation. However, the difference between the Lerner indexes widens ( $L_i^m - L_s^m$ becomes larger) because the reduction in the access fee due to a gain in scale economies is larger under integration.

### 2.2. The downstream duopoly case

In this subsection we characterize the market equilibrium under the same aforementioned situations when there is competition downstream.

*i) Vertically separated duopoly.*

There is vertical separation between the infrastructure manager and the two railway operators. We assume that, in a first stage the infrastructure manager selects the access fee per passenger to equal the average cost of providing the service. In the second stage, the duopolistic operators compete in prices. Solving backwards we obtain the following equilibrium price for each operator as a function of the access fee.

$$p_{1s}(w) = p_{2s}(w) = \frac{A + B(v+w)}{2B - d}. \tag{21}$$

The value of the access fee, where upperscript $d$ denotes duopoly, is equal to,

$$w_s^d = c - \frac{2Bk(A - (B-d)(c+v))}{2B - d - 2Bk(B-d)}. \tag{22}$$

Given symmetry, equilibrium outputs, prices, operator margins and Lerner indices are the same for downstream operators and are given below,.[5]

$$p_s^d = \frac{A + B(c+v) - 2ABk}{2B - d - 2B(B-d)k} \tag{23}$$

$$q_s^d = \frac{B(A - (B-d)(c+v))}{2B - d - 2B(B-d)k} \tag{24}$$

$$p_s^d - w_s^d - v = \frac{A - (B-d)(c+v)}{2B - d - 2B(B-d)k} \tag{25}$$

$$L_s^d = \frac{A - (B-d)(c+v)}{A + B(c+v) - 2ABk} \tag{26}$$

Similarly to the monopoly cases, both price and access fee are decreasing in $k$, noting that the decrease in $w$ is larger than that in $p$ in absolute terms. However, to a lower extent than for the monopoly case.

Comparing the Lerner indices under vertical separation in both the monopoly and the duopoly cases leads to the following result,

**Proposition 2.** Sufficiently large upstream economies of scale will imply a larger Lerner index in case a duopoly is operating downstream, that is, $L_s^d > L_s^m$, for $k > \bar{k} \equiv (\frac{c+v}{\alpha})(\frac{1-\tau}{1-2\tau(1-\tau)}) \equiv (\frac{c+v}{\alpha})\frac{\beta\gamma(\beta+\gamma)}{(\beta^2+\gamma^2)}$.

In case $k = 0$, a monopoly downstream always implies a larger Lerner index, that is, $L_s^d < L_s^m$ always holds.

Proposition 1 prescribes that separation lessens operator's degree of market power. In view of this, Proposition 2 describes what happens when moving from monopoly to duopoly downstream, given that infrastructure is separated from operator activities. In other words, it presents the ordering of the Lerner indices stemming from competition. It can be checked that access fees are lower when there are two rail operators ($w_s^d < w_s^m$). How variations in the access fees are passed through to prices depend on the size of the economies of scale and the degree of product differentiation. The comparison of the Lerner indices is determined by the threshold value $\bar{k}$, which is increasing in the linear output cost parameters ($c$, $v$), decreasing in the maximum willingness to pay ($\alpha$) and in the degree of product differentiation ($\frac{\gamma^2}{\beta^2}$). For example, competition downstream is more likely to bring in more market power when products are perceived as less similar by users, since the condition on the size of economies of scale is weaker.[6]

As the value of $k$ increases sufficiently (above $\bar{k}$), we find that the access fees fall and that the percentage fall under duopoly is larger than under monopoly. The pass through rate to prices is (again) incomplete and, contrary to what one would expect, competition results in increased market power, i.e. the Lerner index under duopoly exceeds that under

3 Notice that some restrictions in the parameters are needed to have non-negative equilibrium quantities: $k < \frac{1}{b}$ and $a > b(c+v)$.

4 $L^m$, $p^m$ and $w^m$ are the Lerner index, price for traveling and access fee, respectively, for the case the access fee is set to maximize infrastructure provider profits. See the Appendix for the precise expressions.

5 Infrastructure marginal cost is given by $mgc_s = c - \frac{4B(A-(B-d)(c+v))k}{2B-d-2B(B-d)k}$.

6 In fact, the Lerner index in the duopoly case is more elastic than that of monopoly with respect to $k$. Thus increases in $k$ induce larger increases in the Lerner index in the case of duopoly. Competition downstream and separation suppose a smaller pass-through.

monopoly. In case economies of scale are not too important (below $\bar{k}$) and because of the already mentioned incomplete pass through to prices, market power weakens with the introduction of competition.

*ii) Partial vertically integrated duopoly*.

The infrastructure manager and railway operator 1 form a vertically integrated firm, while railway operator 2 remains separated. We assume that, in a first stage, the vertically integrated firm selects the access fee per passenger to equal the average cost of providing the service. In the second stage, the integrated firm and the other railway operator compete in prices. The profits of the integrated firm, denoted *VI*, are given by,

$$\begin{aligned} VI &= w(q_1+q_2) - (c(q_1+q_2) - k(q_1+q_2)^2) + (p_1 - w - v)q_1 \\ &= (w-c)q_2 + (p_1 - c - v)q_1 + k(q_1+q_2)^2, \end{aligned} \tag{27}$$

while the railway operator 2 has profits as shown above in (9). Solving for the equilibrium prices as a function of the access fee, i.e. $p_{1i}(w)$ and $p_{2i}(w)$, we have that $p_{2i}(w) > p_{1i}(w)$. Next, by equating $w = c - k(q_1(p_{1i}(w), p_{2i}(w)) + q_2(p_{1i}(w), p_{2i}(w)))$ and solving for $w$ we obtain,

$$w_i^d = c - \frac{2Bk(A-(B-d)(c+v))}{2B-d-(3B-d)(B-d)k}, \tag{28}$$

where $i$ denotes integration and $d$ duopoly. Given that, equilibrium outputs, prices, operator margins and marginal costs of providing the infrastructure service are obtained.[7] We find that the integrated operator 1 serves more passengers at a lower price and gets a higher margin as compared to the operator 2, that is $q_{1i}^d > q_{2i}^d$, $p_{2i}^d > p_{1i}^d$ and $(p_{1i}^d - (c + v - 2k(q_{1i}^d + q_{2i}^d))) > (p_{2i}^d - w_i^d - v)$. Finally, Lerner indices for each operator are,

$$L_{1i}^d = \frac{(2B+d+(B^2+4Bd+d^2)k)(A-(B-d)(c+v))}{(2B+d)(A+B(c+v)) - (A(7B^2-d^2) - B(B-d)^2(c+v))k}, \tag{29}$$

$$L_{2i}^d = \frac{(2B+d-(B^2-d^2)k)(A-(B-d)(c+v))}{(2B+d)(A+B(c+v)) - (A(5B^2+2Bd-d^2) + B(B-d)^2(c+v))k}, \tag{30}$$

where $L_{1i}^d > L_{2i}^d$ for all $k > 0$ and they are identical without scale economies.

Note that the partial vertically integrated duopoly introduces an asymmetry since the access fee affects each operator in a different way. For the non-integrated operator the access fee adds to its marginal costs, while for the integrated operator the marginal cost is $v$ plus the marginal costs of the infrastructure provider (as follows from (27)). This latter term is lower than the access fee due to the existence economies of scale; therefore the integrated operator takes its pricing decision considering a lower total marginal cost as compared to that of the non-integrated operator. Then the equilibrium price of the integrated operator is below that of the non-integrated operator capturing more traffic, and it is in this sense that the integrated structure enjoys a strategic advantage.

Comparing with the vertically separated duopoly, the integrated operator 1 carries more users than it carries when there is separation, that is, $q_{1i}^d > q_s^d$; while for the non-integrated operator 2, that only happens for sufficiently large scale economies, in particular, $q_{2i}^d > q_s^d$ iff $k > d/(B^2 - d^2)$.[8] Finally, more users are served under integration, $Q_i^d > Q_s^d$, where $Q_i^d = q_{1i}^d + q_{2i}^d$ and $Q_s^d = 2q_s^d$.

Regarding the comparisons between Lerner indices we present the following results.

**Proposition 3.** Considering integration, the comparison of Lerner indices between monopoly and duopoly downstream depends on the level of scale economies:

i) The integrated operator will have a larger Lerner index under duopoly, $L_{1i}^d > L_i^m$, if $k > \frac{3\tau-1}{(4\tau+1)b\tau} \equiv \frac{(2\beta-\gamma)(\beta+\gamma)}{5\beta+\gamma}$.
ii) The non-integrated operator will have a larger Lerner index under duopoly, $L_{2i}^d > L_i^m$, if $k < \frac{(1-\tau)(c+v)}{2a} \equiv (\frac{c+v}{\alpha})\frac{\beta(\beta+\gamma)}{2\gamma}$.
iii) In the case $k = 0$, $L_{2i}^d = L_{1i}^d < L_i^m$ always holds.

Proposition 3 shows the effect of introducing competition when one of the operators remains integrated. It turns out that the access fee is lower in the presence of a downstream duopoly because economies of scale are better exploited, total traffic increases. For certain values of economies of scale, the pass-through to prices is larger than the percentage increase in the access fee. This explains why the values of Lerner indices under competition exceed those under monopoly. The existence of economies of scale in infrastructure provision is fundamental for this surprising result to arise. In fact, constant returns to scale would lead us to conclude that competition always reduces the market power of operators under an integrated structure.

**Proposition 4.** Considering duopoly downstream, the comparison of Lerner indices between vertical separation and integration depends on the level of scale economies:

i) For the integrated operator to have a larger Lerner index as compared to the vertical separation situation, i.e. $L_{1i}^d > L_s^d$, is sufficient that $k < \frac{(\tau+1)(2\tau-1)}{b\tau(2(1-\tau)\tau+1)} \equiv \frac{(\beta^2-\gamma^2)(2\beta+\gamma)}{\beta^2+4\beta\gamma+\gamma^2}$.
ii) The non-integrated operator will have a larger Lerner index under vertical integration, that is $L_{2i}^d > L_s^d$, if and only if $k > (\frac{c+v}{a})\frac{(1-\tau)}{\tau} \equiv \frac{\gamma(c+v)}{\alpha}$.

Proposition 4 presents what happens to operators' market power by comparing the separated structure against the structure where one of the operators remains integrated with the infrastructure provider. We noted earlier that the latter case introduces an asymmetry that is advantageous to the performance of the integrated structure. Further note that total output under integration is larger and the access fee is lower than under separation. However, as mentioned above, the price set by the integrated operator is lower than that set by the separated competitor. Because there is an incomplete pass through rate of access fees to prices, we end up with larger Lerner indices under vertical integration, provided certain conditions on the size of economies of scale are met. In other words, Proposition 4 identifies when separation is preferred to integration following the introduction of competition since users would be better off and the market power of rail operators would be lessened.

## 3. An empirical application

In this section we wish to simulate the model using a numerical example in order to complete the analysis and provide further policy conclusions. A calibration process is undertaken in order to replicate the theoretical model, as done in previous papers (see [1,2]). In this paper, we use aggregate data for a rail operator and simulate the case where entry of one additional operator is produced in the rail market. In particular, the data used in the calibration process were taken from the passenger rail market in Spain for 2019 Table 1:

The passenger train-km stands for the train-km run for the long distance and High-Speed-Rail (HSR) services supplied by RENFE in 2019, the Spanish rail operator in the passenger market.[9] We consider this type of traffic, because they are commercial services. On-track competition started in the early months of 2022 and on a limited

[7] All the equilibrium expressions of this section appear in the Appendix.

[8] The condition for $q_{1i}^d > q_s^d$, is $k < \frac{2B^2-d^2}{B^3-Bd^2}$, however $k$ is required to be smaller than $1/b$ and since $1/b < \frac{2B^2-d^2}{B^3-Bd^2}$, the condition always holds. However, for $q_{2i}^d > q_s^d$ it is needed that $d/(B^2 - d^2) < k < 1/b$.

[9] In the empirical part train-km is the demand unit used by infrastructure managers. The latter can also be understood as a supply measure for operators. Note that, train-km units can be converted to passenger-km by assuming that rail operators run with an estimated average load factor in their services, given train capacity, travel times and some contingency factor (see [10], for more details). Note that knowing the route length, the number of passenger-km can be directly expressed in terms of the number of passengers.

**Table 1**
Rail data for 2019.

| | |
|---|---|
| Passenger train-km | 62.3 million |
| Operating cost per train-km | €18.12 |
| Average price per train-km | €34 |
| Own-price elasticity | − 0.8 |
| Cross price elasticity (between rail operators) | 0.2 |

Source: own elaboration from the Observatorio del Ferrocarril 2019 and CNMC (2021). Elasticities from [28]

number of routes. Regional and urban trains are characterized by being offered in terms of Public Service Obligations (PSO) and under a monopoly regime. The EU has established that PSO will have to be offered through franchising systems, but there is no specific time to introduce these competition systems.

In order to recover the parameter $\beta$ in the utility function of the monopoly case we solve the following equation, $\frac{1}{\beta}\frac{34}{62.3} = 0.8$, resulting in $\beta = 0.682$.

Assuming this value of $\beta$, the value for the parameter $\alpha$ can be recovered, $62.3 = \frac{\alpha - 34}{\beta}$. Solving this equation, we obtain that $\alpha = 76.5$.

Next, we need to recover the costs parameters. In particular we split the operating costs from the infrastructure costs. In the case of operating costs, we consider that these are linear costs, assuming there are no economies of scale. Taking data from the Observatorio del Ferrocarril, we know the costs of a commercial train-km and a HSR train-km. Weighting these costs by the percentage of each type of train-km, the value we use for the costs of train-km is €18.3.

Regarding the infrastructure costs, we do not have available data about these type of costs for the Spanish rail network. For this reason we run an econometric regression using data from the Railisa-UIC in the period 2001–2016 that is shown in Table 2. In particular, we use the data from rail infrastructure managers, because they show the costs and the information coming from the rail infrastructure activities necessary to run the rail service. The dependent variable will be the infrastructure rail costs of these eleven rail entities (COSTS). As independent variables we consider the aggregate train-km supply by the rail network (TRAIN-KM) and the number of network km (LENGTH). In order to test for the presence of scale economies in the provision of rail infrastructure activities we introduce the square of train-km. The coefficient of this variable is an approximation to the value of parameter $k$ above. Additionally a time trend (YEAR) is included in the estimation. Unfortunately input prices are not available and cannot be incorporated in our analysis. For this reason we introduce individual effects in our estimation, so that we consider that effects of inputs prices are included in the individual components and hence in the coefficients to be estimated (see [22]). Table 3 shows the results of the estimates using fixed and random effects. In order to select the estimated model, we employ the Hausman test indicating that the random effects model should be employed.

Once values for the model parameters have been obtained, we are ready to calibrate and simulate the outcomes of the various industry structures presented in the previous section. This allows us to offer a detailed assessment of the effects of structural reforms on the degree of market power of rail operators. The results shown in Propositions 1–4 emphasize the orderings of the corresponding Lerner indices by drawing attention to conditions related with the size of economies of scale. The estimated value for parameter k obtained and shown in Table 3 above is rather low, − 0.018. This, together with the other values that are employed, means that the empirical application will report the orderings of Lerner indices under the case of "low sizes of economies of scale" whose intuitions have been given above. Although there are no surprising results in the changes of the degree of market power, the numerical exercise provides a quantitative evaluation of what one expects to happen to user surplus, industry profitability and welfare under different industry structures. Such evidence should prove useful for informed transport policy measures.

We start with the monopoly case, which is calibrated for three different market structures and whose results appear in Table 4. Firstly, we consider both a vertically integrated, and a vertically separated scenarios where the access fee is regulated to cover infrastructure costs as presented in the text above (results appear in the first and second columns in Table 4, respectively); and an unregulated separated structure where the infrastructure manager sets a profit maximizing access fee shown in the Appendix (results are in the third column in Table 4).

The results show that the rankings of Proposition 1 are clearly confirmed. Note that prices are the highest under unregulated separation. The main reason is the double marginalization problem that implies a higher access fee in this regime. This justifies that a separated structure without access fee control notably reduces the traffic volume, decreasing in a significant way both consumer surplus and social welfare with respect to the other regimes. However, note that the Lerner Index in the unregulated separation scenario shows the lowest level indicating that the margin between price and marginal cost is much lower, although this scenario is the worst for consumers and in social terms. Looking at the value of the Lerner Index provides a confusing conclusion. The low level of the Lerner Index in the unregulated scenario is explained, as just noted, by the high access fee, which hugely reduces the margin between the price and the marginal cost. Furthermore, the results for the regulated scenarios are fairly similar, but in the integration scenario the Lerner Index takes a slightly higher value than that obtained in the separation one, but consumer surplus and social welfare are higher too under the integration scenario.

In the case where a new rail company enters the market, two market structures are analyzed, the partial vertically integrated duopoly and a vertically separated duopoly, assuming that infrastructure and rail operations are managed in an integrated (with the incumbent operator) or a separated way, respectively. In both cases we consider that access fees are regulated and they are set in order to recover the whole infrastructure costs. Additionally three alternative exercises are run.

Firstly, we provide the simulation without giving a specific value to parameter gamma in the utility function. Note that this parameter captures the degree of product differentiation between the services supplied by the two rail operators in the duopoly scenario. Secondly, the simulation is run assuming that the parameter for economies of scale in the provision of rail infrastructure is open. And finally the simulation is undertaken under the assumption that the entrant operator introduces a rail service with a lower quality than that of the incumbent, which might reflect an actual practice. The reason is that the entrant can offer a lower number of services than that offered by the incumbent, and users will perceive the service of the entrant as of lower quality. All in all, the purpose of these quantitative analysis is to offer a kind of robustness to the results and conclusions obtained.

*Sensitivity test for gamma.*

Note that $\gamma$ is defined in the interval $[0, \beta]$, where $\gamma = 0$ implies maximum differentiation, i.e., the markets for both products are practically monopolies, and $\gamma$ close to $\beta$ denotes minimum horizontal differentiation and the services provided by the two operators are practically homogeneous. Table 5 shows the results when different values are set for $\gamma$. In particular, we consider the case of maximum differentiation $\gamma \to 0$, an intermediate level of differentiation $\gamma = 0.34$ (i.e. $\gamma = \beta/2$), and the case of minimum differentiation $\gamma \to \beta$.

As expected, when $\gamma$ tends to $\beta$, the results replicate the results of a competitive regime, where consumer surplus is maximized and the Lerner Index tends to zero. However, the fall in profits for the rail industry implies that the social welfare level is the lowest in the most competitive scenario. When $\gamma$ tends to zero, the rail services provided by the two rail operators are almost totally different. In this case, the Lerner Index takes the highest value in both scenarios and consumer surplus is the lowest due to the high prices; however, the large industry profits compensate for the fall in consumer surplus resulting in the highest social welfare level. The comparison across the partial integrated duopoly and a separated duopoly suggests that for low degrees

**Table 2**
Rail infrastructure managers data.

| | Costs (in constant €) | Train-km | Length | # Observ |
|---|---|---|---|---|
| ADIF (Spain) | 3,545,282 | 185,122 | 14,069 | 16 |
| CFR (Romania) | 1,861,997 | 85,757 | 10,774 | 6 |
| FTA (Finland) | 487,306 | 50,163 | 5,886 | 8 |
| NETWORK RAIL (UK) | 4,818,861 | 551,716 | 32,942 | 10 |
| NRIC (Bulgaria) | 5,629,086 | 28,840 | 4,026 | 2 |
| PRORAIL (The Netherlands) | 1,305,501 | 139,477 | 2,847 | 4 |
| REFER (Portugal) | 3,867,311 | 38,639 | 2,776 | 16 |
| RFF (France) | 5,423,109 | 521,226 | 29,463 | 11 |
| SZDC (Czech Republic) | 1,941,767 | 152,761 | 9,471 | 5 |
| TRAFIKVERKET (Sweden) | 1,198,634 | 147,379 | 9,857 | 3 |
| ZSR (Slovak Republic) | 1,026,043 | 44,320 | 3,636 | 2 |

**Table 3**
Estimates of the infrastructure rail costs.

| | Fixed effects | | Random effects | |
|---|---|---|---|---|
| | Coeff. | s.d. | Coeff. | s.d. |
| TRAIN-KM | 17.690 * * | 8.740 | 14.78 * ** | 4.404 |
| LENGHT | 0.2975 * * | 0.148 | 0.112 * ** | 0.034 |
| TIME | 8861 | 18.270 | 30.24 * | 15.630 |
| TRAIN-KM2 | − 0.0298 * * | 0.0140 | − 0.0180 * ** | 0.0060 |
| CONSTANT | − 18683.66 | 36707.92 | − 61402.73 * * | 31379.27 |
| | R2 (overall) = 0.936 | | Wald chi2(3) = 138.82 | |
| # Observat. | 83 | | | |
| Hausman test | Chi2(4) = 8.69, with Prob > chi2 = 0.0694 | | | |

**Table 4**
Monopoly case results.

| | Integration | Separation | Unreg. Separation |
|---|---|---|---|
| Price | 54.15 | 54.41 | 65.46 |
| Access fee | 13.60 | 14.20 | 36.28 |
| Total Train-km | 32.81 | 32.38 | 16.19 |
| Rail operator profits | 714.12 | 714.02 | 178.77 |
| Infr. manag. profits | 0 | 0 | 352.56 |
| Consumer Surplus | 367.29 | 357.54 | 89.38 |
| Social Welfare | 1081.41 | 1071.56 | 620.71 |
| Lerner Index | 0.414 | 0.406 | 0.169 |

of product differentiation, an integrated structure yields small decreases in the degree of market power and modest gains in terms of consumer surplus and social welfare compared to separation.

*Sensitivity test for parameter k.*

Parameter $k$ stands for the size of economies of scale in the provision of infrastructure services. Note that from Table 3 the equation expressing the infrastructure costs (IC) is the following: $IC = 14.78($TRAIN-KM$) - k($TRAIN-KM$)^2$. The value for parameter k obtained in Table 3 will be considered as the central value, and a lower and higher value will be given in order to test the sensitivity of our results. Table 6 displays the results of this analysis, showing that when parameter $k$ increases, the rail prices and access fees fall, provoking a rise in consumer surplus and in industry profitability. However, the Lerner Index increases when economies of scale become more relevant. Given our estimate, economies of scale are not too important and therefore we observe that competition downstream results in lower Lerner indices.

*Sensitivity for quality differences between rail operators.*

In Table 7 we show the results when entry is asymmetric, and quality supplied by the entrant is lower than the quality supplied by the incumbent. It is realistic to assume that the incumbent can supply a service level above that of the entrant, i.e., differences in access time, travel speed and connecting time. Financial or technical restrictions can constrain the entrant to offer a relatively low number of train services, compared to the number of trains supplied by the incumbent. To introduce this assumption we have weighted the parameter $\alpha$ standing for

**Table 5**
Sensitivity checks for γ.

| | Partially Integrated Duopoly | | | Vertically Separated Duopoly | | |
|---|---|---|---|---|---|---|
| | $\gamma \to 0$ | $\gamma = 0.34$ | $\gamma \to \beta$ | $\gamma \to 0$ | $\gamma = 0.34$ | $\gamma \to \beta$ |
| Price incumbent | 53.51 | 46.46 | 31.74 | 54.11 | 46.74 | 31.74 |
| Price entrant | 54.11 | 46.67 | 31.74 | 54.11 | 46.74 | 31.74 |
| Access fees | 13.58 | 13.73 | 13.60 | 13.60 | 13.73 | 13.60 |
| Traff. incumb. | 33.70 | 29.57 | 33.10 | 32.81 | 29.08 | 32.81 |
| Traff. entrant | 32.82 | 28.95 | 32.52 | 32.81 | 29.08 | 32.81 |
| Profits incumb. | 734.59 | 431.66 | 0.0 | 734.58 | 432.70 | 0.0 |
| Profits entrant | 735.11 | 428.75 | 0.0 | 734.68 | 432.70 | 0.0 |
| Consumer surplus | 755.03 | 875.91 | 1468.57 | 734.58 | 865.39 | 1468.56 |
| Social welfare | 2224.73 | 1736.22 | 1468.57 | 2203.74 | 1730.79 | 1468.56 |
| Lerner Index inc. | 0.4297 | 0.3369 | 0.0 | 0.4137 | 0.3183 | 0.0 |
| Lerner Index ent. | 0.4139 | 0.3174 | 0.0 | 0.4137 | 0.3183 | 0.0 |

**Table 6**
Sensitivity checks for $k$.

| | Partially Integrated Duopoly | | | Vertically Separated Duopoly | | |
|---|---|---|---|---|---|---|
| | k = 0.0045 | k = 0.018 | k = 0.0315 | k = 0.0045 | k = 0.018 | k = 0.0315 |
| Price incumbent | 47.20 | 46.46 | 45.68 | 47.27 | 46.74 | 46.19 |
| Price entrant | 47.25 | 46.67 | 46.06 | 47.27 | 46.74 | 46.19 |
| Access fees | 14.51 | 13.72 | 12.89 | 14.52 | 13.73 | 12.91 |
| Traffic incumb. | 28.68 | 29.57 | 30.49 | 28.57 | 29.08 | 29.61 |
| Traffic entrant | 28.53 | 28.95 | 29.38 | 28.57 | 29.08 | 29.61 |
| Profits incumb. | 417.27 | 431.66 | 446.82 | 417.52 | 432.70 | 448.72 |
| Profits entrant | 416.55 | 428.75 | 441.70 | 417.52 | 432.70 | 448.72 |
| Consumer surplus | 837.51 | 875.91 | 917.06 | 835.04 | 865.39 | 897.43 |
| Social welfare | 1671.33 | 1736.22 | 1805.57 | 1670.08 | 1730.79 | 1794.87 |
| Lerner Index inc. | 0.3137 | 0.3369 | 0.3621 | 0.3092 | 0.3183 | 0.3280 |
| Lerner Index ent. | 0.3089 | 0.3174 | 0.3264 | 0.3029 | 0.3183 | 0.3280 |

**Table 7**
Sensitivity for quality differences in rail operator services.

| | Partially Integrated Duopoly | | | Vertically Separated Duopoly | | |
|---|---|---|---|---|---|---|
| | $\sigma = 0.7$ | $\sigma = 0.8$ | $\sigma = 0.9$ | $\sigma = 0.7$ | $\sigma = 0.8$ | $\sigma = 0.9$ |
| Price incumbent | 49.82 | 48.72 | 47.61 | 50.01 | 48.94 | 47.86 |
| Price entrant | 36.19 | 39.70 | 43.21 | 36.24 | 39.76 | 43.27 |
| Access fees | 14.05 | 13.96 | 13.87 | 14.05 | 13.97 | 13.88 |
| Traffic incumb. | 35.19 | 33.29 | 31.40 | 34.85 | 32.92 | 30.98 |
| Traffic entrant | 7.85 | 14.87 | 21.89 | 7.94 | 14.97 | 22.01 |
| Profits incumb. | 620.71 | 553.48 | 490.10 | 621.53 | 554.36 | 491.03 |
| Profits entrant | 31.51 | 113.14 | 245.24 | 32.26 | 114.72 | 247.82 |
| Consumer surplus | 537.59 | 622.37 | 734.168 | 530.25 | 614.18 | 725.13 |
| Social welfare | 1189.81 | 1289.00 | 1469.51 | 1184.04 | 1283.27 | 1463.98 |
| Lerner Index inc. | 0.3705 | 0.3600 | 0.3491 | 0.3565 | 0.3441 | 0.3312 |
| Lerner Index ent. | 0.1109 | 0.1916 | 0.2593 | 0.1121 | 0.1927 | 0.2602 |

the willingness to pay for the rail services supplied by the entrant in the utility equation by the coefficient $\sigma$, where $\sigma < 1$.[10] We have considered three alternative values.

It is clear that the larger the quality difference, the lower the value of the Lerner Index for the rail entrant. However, as expected, the low quality of the rail entrant leads to a reduced value of consumer surplus and social welfare. As the service quality of the entrant increases so does its degree of market power, yet the value of the Lerner Index for the incumbent falls. Interestingly, both consumer surplus and social welfare increase.

## 4. Conclusions and managerial implications

This paper has examined changes in the degree of market power downstream in vertically linked industries, where access fees are regulated. The novelty, relative to the received literature, lies in the consideration of economies of scale at the upstream level. The analysis has distinguished whether there is a monopoly or a duopoly structure downstream and also whether the upstream firm is integrated or not with a downstream firm. These are intrinsic elements that characterize the rail industry and the conclusions that we reach may be useful for policy evaluation regarding market power, user surplus and welfare. This theoretical setting is of general applicability to regulated network industries. The results are found to crucially depend on the size of economies of scale, showing that market power changes in the railway industry are explained by a better exploitation of such economies enjoyed by infrastructure providers and harmless for consumers. We also provide an empirical application to the case of the Spanish railway system. Our analysis throws some interesting managerial implications. Firstly, the introduction of competition may not weaken the degree of market power of the incumbent operator. Secondly, consumers will benefit the most from competition when the service quality of the entrant is closer to the incumbent's and economies of scale are important. Thirdly, in the absence of competition, an integrated structure is preferable although the degree of market power may be rather high. Fourth, regulators should be aware that when implementing a given policy both market power and user surplus may increase at the same time. Fifth, access fee regulation according to average cost has implications on competition downstream when one operator is integrated with the upstream infrastructure provider. These conclusions should be helpful in the design of rail transport policies.

## Data Availability

Data will be made available on request.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[10] One way to introduce asymmetries between operators is to assume different maximum willingness to pay. This can be implemented by setting, $\alpha_1 = \alpha$ and $\alpha_2 = \sigma\alpha$ in expression (2) where $\sigma < 1$ and the difference in quality between the incumbent and the entrant operators can be approximated by $\alpha_1 - \alpha_2 = (1 - \sigma)\alpha$. That is, a larger $\sigma$ implies a lower difference in quality in favor to the incumbent. Note that asymmetries in the demand intercepts have a clear interpretation in terms of vertical differentiation between products as put forward by [16].

## Appendix A. Equilibrium expressions

In this appendix we provide the equilibrium expressions for both, a vertically separated monopoly when the infrastructure manager sets a profit maximizing access fee, i.e. the *Vertically separated monopoly with a profit maximizing* $w$ , and also for the *Partially vertically separated duopoly* case.

*a) Vertically separated monopoly with a profit maximizing* $w$ .

The case presented here is a two-stage game where in the first stage the infrastructure manager sets the access fee per passenger to maximize profits and in the second stage the monopolist operator chooses the profit maximizing price. Solving backwards, the price that maximizes the monopolist operator profits for any given $w$ is the one in (9) in the text. Then, the access fee $w$ that maximizes the upstream monopolist profits is given by

$$w^m = c + \frac{(1-bk)(a-b(c+v))}{b(2-bk)} \tag{A.1}$$

After substitution in the price expression appearing in (9),

$$p^m = \frac{a+b(c+v)+2a(1-bk)}{2b(2-bk)} \tag{A.2}$$

Note that both, $w^m$ and $p^m$ are decreasing in $k$ and the access fee decreases more (the double exactly). Equilibrium output, operator margin and Lerner index at equilibrium are, respectively:

$$q^m = \frac{a-b(c+v)}{2(2-bk)} \tag{A.3}$$

$$p^m - w^m - v = \frac{a-b(c+v)}{2b(2-bk)} \tag{A.4}$$

$$L^m = \frac{a-b(c+v)}{a+b(c+v)+2a(1-bk)} \tag{A.5}$$

*b) Partial vertically separated duopoly*.

The equilibrium prices as a function of $w$ are:

$$p_{1i}(w) = \frac{2B(A+B(c+v)+d(w-c)-4A(B-d)k)+(d+2(B-d)^2k)(A+B(v+w))}{(2B+d)(2B-d-2(B-d)^2k)} \tag{A.6}$$

$$p_{2i}(w) = \frac{2AB+Bd(c+v)+d^2(w-c)-4AB(B-d)k+B(2B-d-4(B-d)^2k)(w+v)+(d+2(B-d)^2k)(A+B(v+w))}{(2B+d)(2B-d-2(B-d)^2k)} \tag{A.7}$$

$$p_{2i}(w) - p_{1i}(w) = \frac{(B-d)((2B-d)(w-c)+4B(A-(B-d)(v+w))k)}{(2B+d)(2B-d-2(B-d)^2k)}. \tag{A.8}$$

Equilibrium outputs, prices, operator margins and marginal costs of providing the infrastructure service as follows,

$$q_{1i}^d = \frac{B(2B+d+k(B^2-d^2))(A-(B-d)(c+v))}{(2B+d)(2B-d-k(3B-d)(B-d))} \tag{A.9}$$

$$q_{2i}^d = \frac{B(2B+d-k(B^2-d^2))(A-(B-d)(c+v))}{(2B+d)(2B-d-k(3B-d)(B-d))}, \tag{A.10}$$

$$p_{1i}^d = \frac{(2B+d)(A+B(c+v))-k(A(7B^2-d^2)-B(B-d)^2(c+v))}{(2B+d)(2B-d-k(3B-d)(B-d))} \tag{A.11}$$

$$p_{2i}^d = \frac{(2B+d)(A+B(c+v))-k(A(5B^2+2Bd-d^2)+B(B-d)^2(c+v))}{(2B+d)(2B-d-k(3B-d)(B-d))}, \tag{A.12}$$

$$p_{1i}^d - (c-2k(q_{1i}^d+q_{2i}^d)) - v = \frac{(2B+d+(B^2+4Bd+d^2)k)(A-(B-d)(c+v))}{(2B+d)(2B-d-(3B-d)(B-d)k)}, \tag{A.13}$$

$$p_{2i}^d - w_i^d - v = \frac{(2B+d-(B^2-d^2)k)(A-(B-d)(c+v))}{(2B+d)(2B-d-(3B-d)(B-d)k)}, \tag{A.14}$$

$$mgc_i = c - \frac{4Bk(A-(B-d)(c+v))}{2B-d-k(3B-d)(B-d)}. \tag{A.15}$$

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