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How “efficient” are intercity railway prices and frequencies in Europe? Comparing a corridor in Belgium and in France

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FACULTY OF ECONOMICS AND BUSINESS

DISCUSSION PAPER SERIES DPS18.07

JULY 2018

How “efficient” are intercity railway prices and frequencies in Europe? Comparing a corridor in Belgium and in France

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July 4, 2018

Abstract: This paper studies the efficient pricing of medium distance passenger rail in Europe. Current fares and frequencies are compared with three alternatives: First-Best where road congestion is internalized, Second-Best where no road tolls are implemented and Third-Best where a maximum rail deficit is also imposed. We find that Second-Best fares depend strongly on the non-internalized road congestion and on the price elasticity of the passengers, complicating the derivation of a national or regional fare structure. Second-Best achieves a significant share of the First-Best benefits but adding a budget constraint makes Second-Best solutions difficult to implement for some corridors.

Key words: Regional rail; Pricing; Optimal Capacity; Distortions; Externalities

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[2] For useful comments on a previous version we would like to thank Jan Brueckner, Chau Man Fung, and participants at the Annual Conference of the International Transportation Economics Association (ITEA) in Santiago (Chile), June 2016, and at the Department of Economics, University of California, Irvine (USA), September 2016.

1. Introduction

In Asia and the EU, railways are a non-negligible passenger transport mode. In Japan, 30.5 per cent of passenger kilometers were made by rail while in China and India resp. 25 per cent and 13 per cent of passenger kilometer were made by rail (IEA & UIC, 2015). In Europe, the share is smaller, ranging from 0.9 per cent in Greece to 17.1 per cent in Switzerland (Source: Eurostat[3]). In rail operations one distinguishes often between urban rail, regional rail and long distance high speed rail. In this paper we focus on the regional rail in Europe connecting several cities (30 to 150 km), where one of the dominant transport motives is commuting. 17 per cent of the commuters to Brussels use rail (Verhetsel, et al., 2007). For metropolitan areas the encouragement of the modal shift from car to rail is seen as an important component of the transport and environmental policy package.

The last decennia, there has been academic interest in the properties of the cost function of rail, in the vertical separation of infrastructure and operation as well as in the regulation of public and private rail companies. This research was mainly motivated by the promises of more competition in this sector. The cost efficiency effects of this liberalization has been studied intensively using mainly firm level data. We do not study this competition but rather study the optimal pricing structure for regional rail operations. How to implement the optimal pricing structure is not studied. Important in our study of pricing is that we take into account the unpriced road congestion as this is one of the main motivations for public rail subsidies. We look into medium distance corridors connecting two cities to a metropolitan area and this in two countries. To travel from the city where they live to destination, the individuals choose between two modes and two periods, peak and off-peak. These modes are private car and rail. We

[3] http://ec.europa.eu/eurostat/web/transport/data/database

distinguish different groups of representative travelers that differ in income, value of time and modal preferences. For each corridor we analyze the efficiency of current rail prices.

More specifically we focus on the following four research questions. First what are the second best rail fare and corresponding frequency for a rail trip in peak and off-peak and how it deviates from the first best price and frequency? The first best pricing structure is not without interest as several EU countries contemplate the introduction of road pricing.

Second what are the underlying forces of the second best price, how does it depend on density, aversion to crowding, value of time, road congestion and frequency. Structuring the railway fares in function of a few parameters is useful when the railway company has to present general fare setting principles that can be applied to the different corridors it is operating.

Third, as most rail companies operate under a strict maximum deficit constraint, what mark-ups are optimal to reach the deficit constraint? Fourth, are international differences in rail prices based on objective differences in the second best optimal charges?

We analyzed present and optimal prices in comparable corridors in two countries: Belgium and France. Current rail prices differ by more than 50 per cent for comparable journeys and show a different profile of discounts for some categories of customers. Most current prices are above the second best optimal prices. In most European countries the main reason is the diversion of travelers away from the road mode. The exception is France where the current *péage* on the motorway result in overpricing of the use of cars so that the second best rail prices are above the marginal cost.

Passenger rail is a sector that is not very transparent in terms of data and this explains the main limitations of this study. First we focus on one isolated corridor per country and neglect other network aspects. Second we focus only on passenger rail operations taking as given the charges for the use of the infrastructure. We also assume full control of all rail prices and all frequencies and work with given unit operation cost data. So regulatory issues and possible cost inefficiency reactions are neglected. Finally, the cost and passenger volume data are often secret so we need many assumptions to complete the data for the reference situation.

Section 2 reviews the literature. Section 3 presents the analytical model that is used to compute the optimal first and second best rail prices. Section 4 presents the most important data. Section 5 analyzes in depth the results for a corridor in one country (Belgium). Section 6 broadens the analysis to a comparison with one corridor in France. Section 7 concludes.

2. Literature Review

We restrict the analysis to the pricing of the medium distance passenger rail trips. The freight market, the very short distance (tram and urban rail) and the long distance trips (HSR) are characterized by different production costs and market conditions. The setting of optimal rail prices faces three types of issues.

The first issue has to do with the absence of competition: often there is only one supplier whose costs are uncertain. This requires looking for good production cost information and designing a good regulation scheme. Optimal prices will in general involve optimal deviations of the marginal costs so as to meet budget constraints (Ramsey-Boiteux pricing) together with the right incentive constraints.

Second issue is the knowledge of the marginal costs of different types of products offered by a rail infrastructure manager and a rail operator. The third issue is to consider deviating from marginal cost pricing not only to meet budget constraints but also to take into account distortions on other transport markets.

In his review, Nash (2015) did not find very clear effects of liberalization on production costs, it is case dependent. In this paper we focus on the operation of rail for given rail infrastructure charges. So the “efficient” rail passenger prices we compute will be conditional on the infrastructure charges and the present unit operation costs.

Determining the marginal cost of rail is a paper topic on its own. Most production cost studies for rail operation concentrate on aggregate output indicators like total seat kilometers or total passenger kilometers supplied. These studies allow to check for production efficiency (see Cantos, et al. (2010)) and for returns to scale and can compute the marginal cost of an extra passenger kilometer somewhere on the network.

We take a more micro-or engineering approach as we consider one corridor only. The marginal cost of a passenger can be computed in two ways (Kraus (1991), Jara-Díaz & Gschwender (2003), Jansson, et al. (2015)). Simplest is to assume a rule of thumb for the accommodation of new passengers that trade-off between the cost of additional vehicles and the additional crowding. This approach was used for urban rail and bus by Parry & Small (2009) as well as by Kilani, et al. (2014). We use a more explicit approach and set the marginal cost of a passenger equal to the external crowding cost. The external crowding cost is then the result of simultaneous optimization of the frequency and the fare where crowding, schedule delay and congestion on the rail network are compared with the operating and rental cost of an additional train. This is also the methodology followed by Basso & Silva (2014) for urban busses and by de Palma, et al. (2015) and de Palma, et al. (2017) in a theoretical setting.

The third issue in deriving efficient rail prices is to take into account the effects of rail prices on other distorted markets. The two distortions that have received most attention are the unpriced road congestion (de Palma, et al., 2015) and highly taxed labour market. In most countries road congestion is not priced and this implies that the optimal rail prices are lower than the marginal social costs. Lower rail prices allow to reduce road congestion by substituting car trips by rail trips. The optimal rail fare will then be lower, the better is the substitution between the two modes and the more important is the unpriced externality. Labour supply is heavily taxed and when an increase of rail prices decreases labour supply, there will be an additional welfare loss that can be important. This may call for differentiation of fares between active and non-active passengers (Van Dender, 2003) and for the use of toll revenues to reduce labour taxes ((Parry & Bento (2001), Diaz & Proost (2014)). As we only study the optimization of rail fares, the net effect on labour supply will be marginal so that we do not need to address this issue.

Optimal prices for rail were computed for the Netherlands by Van Vuuren (2002). Van Vuuren, contrary to us, uses an aggregate country level perspective, has no explicit frequency optimization and does not consider the distortions on other markets. Parry & Small (2009) look for optimal urban rail prices for metropolitan areas like London. They found very low optimal prices for peak (90 per cent subsidized) and off-peak service (78 per cent subsidized). In the peak period, this was mainly due to the large substitution effect with unpriced peak car use. In the off-peak period, this was mainly due to the economies of scale and the positive externality of more frequent service. Our results are in line with this paper, except that we deal with medium distance traffic and consider explicitly different user groups. These different user groups allow us to study rail fares that are optimally differentiated to reach budget constraints.

3. Analytical model

The model is a partial equilibrium model focusing on the passenger transport market. This is appropriate as long as the supply of labour is not affected by the transport costs and as long as we are not interested in the income distribution aspects. Locations are fixed. The total price elasticity for commuting trips that we use is very low so that we can focus on the transport market only.

3.1. Model assumptions

We consider a simple intercity transport system connecting three cities, A, B and D (see Figure 1). Individuals live in cities A and B and travel to a unique destination, city D. City D can be seen as a metropolitan area. City A is located further from the destination than city B. The distance by road between A and B is d_{AB}^{road}, between B and D d_{BD}^{road} and between A and D $d_{AD}^{road} = d_{AB}^{road} + d_{BD}^{road}$. The distance by rail between A and B is d_{AB}^{rail}, between B and D d_{BD}^{rail} and between A and D $d_{AD}^{rail} = d_{AB}^{rail} + d_{BD}^{rail}$.

[Figure 1 here]

3.1.1. Consumers surplus

The whole population living in areas A and B is made of I groups of homogeneous individuals, $i = 1, \ldots, I$. $N_{i,j}$ individuals in group i live in city j. Consequently, $\sum_{i=1}^{I} N_{i,j}$ individuals live in city $j = A, B$. The I groups differ with respect to their value of time, α_i, their income, R_i,[4] and their travel preferences.

To travel from the city where they live (A or B) to destination (D), the individuals choose between two modes and two periods. These modes are $m = CAR$ (auto) and $RAIL$ (rail). The two periods are denoted by superscript $k = P$ (peak) and O (off-peak). The length of time of period k is h^k.

$x_{i,j}^{m,k}$ is the number of trips made by the representative user of group i departing from city j by mode m during period k. $X_j^{m,k} = \sum_{i=1}^{I} N_{i,j}\, x_{i,j}^{m,k}$ is the total volume of trips departing from city j made by mode m during period k. $q_{i,j}$ is the quantity of a numeraire or general consumption good consumed by the representative user of group i living in city j. Consequently, the utility function of the representative user of group i living in city j is

[4] Value of time and revenue are correlated.

$$U_{i,j} = U_{i,j}\left(q_{i,j}, \{x_{i,j}^{m,k}, m = CAR, RAIL; k = P, O\}\right). \quad (1)$$

We assume that U is increasing and quasi-concave in each of its arguments, implying that travel by different modes and times of day are imperfect substitutes.

3.1.2. Transport supply

Rail supply - $V^{RAIL,k}$ trains depart from city A during period k. Each of those trains stops by city B, where users from city B can board the train but where no user from city A alight from the train, because their destination is D. Because it would be expensive to daily adjust the composition of trains between periods, the composition of a train is assumed homogeneous across periods: each run offers S^{RAIL} seats. Consequently, during period k, the train company offers $Y^{RAIL,k} = V^{RAIL,k} \times S^{RAIL}$ seats from city A to the destination. The occupancy rate in period k between A and B is $o_{AB}^{RAIL,k} = X_A^{RAIL,k}/Y^{RAIL,k}$, and between B and D, $o_{BD}^{RAIL,k} = \left(X_A^{RAIL,k} + X_B^{RAIL,k}\right)/Y^{RAIL,k}$.

To operate $V^{RAIL,k}$ runs during period k, the train company needs (at least) $\breve{V}^{RAIL}$ physically distinct trains, with

$$\breve{V}^{RAIL} \equiv max\{2 \times \overline{tt}_{AD}^{RAIL} \times V^{RAIL,P}/h^P\,; 2 \times \overline{tt}_{AD}^{RAIL} \times V^{RAIL,O}/h^O\}$$

where $\overline{tt}_{AD}^{RAIL}$ is the travel time of rail between A and D. Because the peak train frequency is always higher or equal to the off-peak train frequency, we assume that the number of trains constraint only depends on the number of runs during the peak period: $\breve{V}^{RAIL} = 2 \times \overline{tt}_{AD}^{RAIL} \times V^{RAIL,P}/h^P$. The train agency production cost is

$$TC^{RAIL} = \mu_0^{RAIL} + \breve{V}^{RAIL} \times \mu_1^{RAIL}$$

$$+(V^{RAIL,P} + V^{RAIL,O}) \times \left(\mu_2^{RAIL} + \upsilon^{RAIL} \times p^{fuel} \times d_{AD}^{rail}\right) \quad (2)$$

Where μ_0^{RAIL} is the fixed cost of the rail infrastructure, $\breve{V}^{RAIL} \times \mu_1^{RAIL}$ is the rental cost of rolling stock needed, and $(V^{RAIL,P} + V^{RAIL,O}) \times \left(\mu_2^{RAIL} + \upsilon^{RAIL} \times p^{fuel} \times d_{AD}^{rail}\right)$ is the operating cost. μ_1^{RAIL} is the cost per train rented, it is a function of the capacity of the train, S^{RAIL}. $V^{RAIL,P} + V^{RAIL,O}$ is the number of runs operated, μ_2^{RAIL} is the cost per run (including the drivers wages). υ^{RAIL} is the consumption of fuel per train vehicle kilometer, and f is the price of fuel. $p^{fuel} = \bar{p}^{fuel} + \kappa^{fuel}$, where κfuel is the tax on fuel. The collected taxes on fuel are a revenue for the government.[5]

The fare for a train journey departing from j during period k in class m is $p_j^{RAIL,k}$. Therefore, the revenue of the train company is

$$\Pi^{RAIL} = \sum_{j=A,B} \sum_{k=P,O} X_j^{RAIL,k} \times p_j^{RAIL,k} - TC^{RAIL}.$$

Road supply - The road capacity is s_{AB}^{road} between A and B, and s_{BD}^{road} between B and the destination.

Car supply - $V_{i,j}^{CAR,k}$ cars carrying user from group i depart from city j during period k, with $V_{i,j}^{CAR,k} = X_{i,j}^{CAR,k}$ meaning that the car occupancy rate equals one over periods, users types, and origins. A toll is also imposed on each car: $\tau_{AB}^{CAR,k}$ between A and B, and $\tau_{ABD}^{CAR,k}$ between B and$D$. Consequently, the fare paid by a car coming from A is $\tau_A^{CAR,k} = \tau_{AB}^{CAR,k} + \tau_{BD}^{CAR,k}$, and by a car coming from B, $\tau_B^{CAR,k} = \tau_{BD}^{CAR,k}$. The fuel consumption of a car between an origin j and destination D is $\upsilon^{CAR} \times d_{jD}^{roaD}$. υ^{CAR} is the car consumption of fuel per kilometer.

3.1.3. Users costs

[5] However, this tax on fuel is not considered as an instrument later in the analysis.

Depending on the mode they choose, individuals incur a variety of monetary and non-monetary costs when traveling (Ivaldi & Seabright, 2003). The monetary travel costs are obvious but there are different levels of precision for the non-monetary costs. All individuals incur a "free" travel time, depending on their value of time and on the travel length. Road travelers also incur a congestion cost which increases with the number of vehicles on road. Train users experience schedule delay and discomfort costs. The train service is characterized by discrete departure and arrival times at destination. Users have to choose within a finite set of possible arrival times. If the effective arrival time does not coincide with the preferred arrival time, the traveler incurs schedule delay costs. The comfort in train decreases with the occupancy rate: less seats are available, some travelers may have to stand during the trip... Finally, train users also incur a lateness cost. Indeed, late arrivals happen when there are too many trains on the line at the same time. Consequently, there is a potential lateness time which increases with the number of trains on rail during the same period, and decreases with the rail capacity.

When individuals make a journey, they incur two types of costs: monetary and non-monetary cost. These costs are described below.

Monetary user cost - $MUC_j^{m,k}$ is the monetary cost per user from city j using mode m during period k. The monetary costs for train users is the fare ticket, $p_j^{m,k}$. Car travelers incur a different type of monetary cost. Indeed, they have to pay a toll, a fixed cost of using a car and the fuel consumption.

$$MUC_j^{RAIL,k} = p_j^{m,k}$$

$$MUC_j^{CAR,k} = \tau_j^{CAR,k} + \upsilon^{CAR} \times p^{fuel} \times d_{jD}^{road}.$$

We assume that the labour supply is not really affected by transport pricing. The budget equation of the representative user of group i living in city j can be written

$$R_{i,j} \geq q_{i,j} + \sum_m \sum_k MUC_j^{m,k} \times x_{i,j}^{m,k} \tag{3}$$

where $R_{i,j}$ stands for the budget of the representative user of group i living in city j. $q_{i,j}$ is a numeraire good, its price equals 1.

Non-monetary user cost - When traveling, users incur non-monetary costs which are mainly related to the time dimension: the length of the journey, the potential lateness, the utility of time when traveling in discomfortable conditions...

Free travel time cost - The free travel time between $j = A,\ B$ and D with mode m, $\overline{tt}_{jD}^{m}$, is the ratio of the distance to the average speed. The cost of travel time, denoted $time$, varies across modes and groups because individuals have different values of time,α_i:

$$time_{i,j}^{m} = \alpha_i \times \overline{tt}_{jD}^{m}. \tag{4}$$

Road congestion - The road congestion also includes road unreliability. The extra travel time $\overline{\overline{tt}}^{k}$ cost due to congestion depends on the number of vehicles which use the road at the same period, and on the capacity of the road, s_{AB}^{road} between A and B, and s_{BD}^{road} between B and the destination. We use a linear function of the volume/capacity ratio.

$$\overline{\overline{tt}}_{AB}^{k} = \theta^{road} \times \frac{\sum_{i=1}^{I} V_{i,A}^{CAR,k}}{s_{AB}^{road} h^k}$$

$$\overline{\overline{tt}}_{BD}^{k} = \theta^{road} \times \frac{\sum_{i=1}^{I} V_{i,A}^{CAR,k} + \sum_{i=1}^{I} V_{i,B}^{CAR,k}}{s_{BD}^{road} h^k}$$

$$\overline{\overline{tt}}_{AD}^{k} = \overline{\overline{tt}}_{AB}^{k} + \overline{\overline{tt}}_{BD}^{k}$$

θ^{road} is the congestion parameter. The cost of congestion for a journey from city j, $cong_j$, is

$$cong_j = \theta_i \times \overline{\overline{tt}}_{jD}^{k}. \tag{5}$$

Rail unreliability cost - The train free travel time equals the ratio of the distance over the average speed. However, late arrivals happen when there are too many train on the line at the same time. Consequently, there is a potential lateness time which increases with the number of trains on rail during the same period, and decreases with the rail capacity, s^{RAIL}. The rail capacity is given and cannot be improved. Its cost is included in μ_0^{RAIL} in Equation (2). The average lateness is given by

$$lateness^{RAIL,k} = \theta^{RAIL} \times \frac{(\overline{tt}_{AB}^{RAIL} + \overline{tt}_{BD}^{RAIL})V^{RAIL,k}}{s^{RAIL}h^k}$$

where θ^{RAIL} is the extra lateness time due to the presence of an extra train per hour on a given rail infrastructure. The cost of this lateness is the unreliability cost, $unrel$

$$unrel_i^{RAIL,k} = \alpha_i \times lateness^{RAIL,k}. \tag{6}$$

The increase in lateness costs can also be seen as a scarcity indicator for the rail network. When the ratio of the number of trains becomes too high compared to the track capacity, there is a need to rethink the priority or scheduling of the trains as well as the capacity of the tracks. Nilsson (2002) provides a methodology for this.

Schedule delay cost - The train service is characterized by discrete departure and arrival time at destination. Users have to choose within a finite set of possible arrival times. If the effective arrival time does not coincide with the preferred arrival time, the traveler incurs schedule delay cost. This schedule delay cost is a linear function of the inverse of the frequency:

$$sched_i^{RAIL,k} = \alpha_i \times \delta \times \frac{h_k}{V^{RAIL,k}}. \tag{7}$$

In the $\alpha - \beta - \gamma$ schedule framework (Arnott, et al., 1993), assuming that preferred arrival times are uniformly distributed for each group, $\alpha_i \times \delta = \frac{\beta_i \gamma_i}{2(\beta_i + \gamma_i)}$. β_i and γ_i can be written as linear function of the value of time, α_i.

Rail discomfort - The comfort in train is a linearly[6] decreasing function of the occupancy rate: less seats are available, some travelers may have to stand during the trip (Tirachini, et al., 2013).

$$discom_{i,A}^{RAIL,k} = \alpha_i \times \eta^{RAIL} \times \left(o_{AB}^{RAIL,k} \times \overline{tt}_{AB}^{RAIL} + o_{BD}^{RAIL,k} \times \overline{tt}_{BD}^{RAIL}\right)$$
$$discom_{i,B}^{RAIL,k} = \alpha_i \times \eta^{RAIL} \times o_{BD}^{RAIL,k} \times \overline{tt}_{BD}^{RAIL} \,. \tag{8}$$

η^{RAIL} is the crowding cost parameter.

Final non-monetary user cost – Equations (4), (5), (6), (7) and (8) give $NMUC_{i,j}^{m,k}$, the non-monetary cost per user of group i living in city j and using mode m during period k

$$NMUC_{i,j}^{CAR,k} = time_{i,j}^{CAR,k} + cong_{i,j}^{CAR,k}$$
$$NMUC_{i,j}^{RAIL,k} = time_{i,j}^{RAIL,k} + unrel_{i,j}^{RAIL,k} + discom_{i,j}^{RAIL,k} + schedul_{i,j}^{RAIL,k}.$$

The aggregate non-monetary users costs are written

$$CONG^{CAR,k} \equiv \sum_n \sum_r N_{n,r} \times x_{n,r}^{CAR,k} \times cong_{n,r}^{CAR,k}$$

$$DISCOM^{RAIL,k} \equiv \sum_n \sum_r N_{n,r} \times x_{n,r}^{RAIL,k} \times discom_{n,r}^{RAIL,k}$$

$$UNREL^{RAIL,k} \equiv \sum_n \sum_r N_{n,r} \times x_{n,r}^{RAIL,k} \times unrel_{n,r}^{RAIL,k}$$

$$SCHED^{RAIL,k} \equiv \sum_n \sum_r N_{n,r} \times x_{n,r}^{RAIL,k} \times schef_{n,r}^{RAIL,k}.$$

3.1.4. Other externalities

[6] Linearity is empirically supported by Jara-Díaz and Gschwender (2003), Haywood and Koning (2015) and Haywood et al. (2017).

Each mode also produces negative externalities other than congestion and discomfort, mainly due to pollution and accidents. These externalities are modeled as a linear function of the vehicles-kilometers:

$$EXT^{RAIL,k} = \iota^{RAIL} \times V^{RAIL,k} \times d_{AD}^{rail}$$

$$EXT^{CAR,k} = \iota^{CAR} \times \left(V_A^{CAR,k} \times d_{AD}^{road} + V_B^{CAR,k} \times d_{BD}^{road}\right) \tag{9}$$

where ι^m is the combined pollution and accident external cost per vehicle kilometer of mode m.

3.2. First-best optimum

The first-best optimum is obtained by maximizing the aggregate social welfare under constraint of user optimum. The aggregate social welfare, Ω, is defined as the sum of the total individual surplus, the rail company profit, the revenue of fuel tax and road tolls, minus the total individual non-monetary cost, the road capacity cost, and the pollution and accidents costs

$$\begin{aligned}
\Omega = \sum_i \sum_j N_{i,j} \times \left[\underbrace{U_{i,j}}_{Users\ surplus} - \underbrace{\sum_m \sum_k x_{i,j}^{m,k} NMUC_{i,j}^{m,k}}_{Users\ non-monetary\ costs} \right] \\
+ \underbrace{\Pi^{RAIL}}_{Rail\ company\ profit} - \underbrace{\sum_m \sum_k EXT^{m,k}}_{Pollution\ and\ accidents\ externalities} \\
+ \underbrace{\kappa^{fuel} \times \left[(V^{RAIL,P} + V^{RAIL,OP}) \times \upsilon^{RAIL} \times d_{AB}^{RAIL} + \sum_k \sum_j V_j^{CAR,k} \times \upsilon^{CAR} \times d_{jD}^{road} \right]}_{Revenue\ of\ the\ fuel\ tax} \\
+ \underbrace{\sum_k \sum_j V_j^{CAR,k} \times \tau_j^{CAR,k}}_{Revenue\ of\ the\ road\ tolls}.
\end{aligned} \tag{10}$$

We consider two sets of constraints. The first set of constraints ensures that each individual does not consume more than his revenue allows. The revenue of the representative individual of group i living in city j has to be higher or equal to his expenditures. The corresponding inequality is given in Equation (3).

The second set of constraints ensures that the individual behavior is rational. The rationality implies that individuals maximize their utility, and that the marginal utility of consumption of a good, which is also the willingness to pay for this good, equals the cost of consumption of this good, defined as the sum of the non-monetary user cost and the monetary user cost:

$$\frac{\partial U_{i,j}}{\partial x_{i,j}^{m,k}} = NMUC_{i,j}^{m,k} + MUC_{i,j}^{m,k}$$

$$\frac{\partial U_{i,j}}{\partial q_{i,j}} = 1. \tag{11}$$

We assume that the willingness to pay is higher for a peak journey than for an off-peak journey. This assumption is consistent with the observation that travelers are willing to support higher non-monetary costs during peak periods. The main consequence is that more users travel during peak periods.

We maximize the aggregate social welfare (Equation (10)) subject to the revenue constraints (Equation (3)) and the constraints of user equilibrium in each mode and each period (Equation (11)). This social welfare problem can be solved by maximizing the following Lagrangian function

$$\mathcal{L} = \Omega + \underbrace{\sum_i \sum_j \lambda_{i,j}\left(R_{i,j} - q_{i,j} - \sum_m \sum_k x_{i,j}^{m,k} MUC_{i,j}^{m,k}\right)}_{Lagrangian\ revenue\ constraints} \tag{12}$$

where $\lambda_{i,j}$ is the Lagrangian multiplier associated with the revenue constraint of representative individual of group i living in city j. We assume that there are no other distortions in the economy than those considered in our model. Differentiating $\mathcal{L}$ with respect to $\lambda_{i,j}$ gives

$$\frac{\partial \mathcal{L}}{\partial \lambda_{i,j}} = 0 \Leftrightarrow R_{i,j} = q_{i,j} + \sum_{m}\sum_{k} x_{i,j}^{m,k} MUC_{i,j}^{m,k}, \forall i,j.$$

The equation above means that the revenue is fully spent.

The road tolls and rail fares, the road capacity, the train size and frequencies are chosen to maximize the aggregate social welfare. Detailed calculations are available in appendices. The following notation is used: $\dot{Z}_W^{m,r} = \frac{\partial Z^{m,r}}{\partial W}$ is the derivative of $Z^{m,r}$ with respect to W.

3.2.1. Optimal rail supply and fare

Differentiating $\mathcal{L}$ in Equation (12) with respect to the number of train trips taken by the representative user, $x_{i,j}^{RAIL,k}$, setting to zero and rearranging give the optimal rail fare

$$p_j^{RAIL,k} = \frac{\partial o_j^{RAIL,k}}{\partial X_j^{RAIL,k}} \times DIS\dot{C}OM_{o_j^{RAIL,k}}^{RAIL,k}, \forall k,j. \tag{13}$$

This equation shows that the optimal fare charged on train users equals the marginal social cost of discomfort imposed on train users. To understand the optimal fare one needs to start from the idea that the frequency and size of the train is given. The cost of an extra passenger is then the discomfort for the other train users which is mainly crowding. There is a close parallel with the pricing of road congestion: an extra car will, for given road capacity, delay all other cars. There is one important difference: capacity of trains can be adapted easily by increasing the size and the frequency of trains. As the optimal frequency balances the reduction in crowding costs with the cost of frequency, the optimal rail fare equals to some extent also the marginal cost of bringing in an extra train.

Equation (13) implies $p_A^{RAIL,k} > p_B^{RAIL,k}$: train users traveling from more distant city A pay a higher fare than those traveling from city B. An additional user from A and from B equally raise the aggregate cost of discomfort imposed on train users between B and D. But the additional user from A also increases the aggregate cost of discomfort imposed on train users between A and B.

It seems reasonable to assume that both the number of users and the occupancy rate are higher during the peak period than during the off-peak period. If these two assumptions hold, the marginal social cost of discomfort and also the train fare are higher during peak period than during off-peak: $p_j^{RAIL,P} > p_j^{RAIL,O}$.

Differentiating $\mathcal{L}$ with respect to the number of train runs made during period k, $V^{RAIL,k}$, and setting the derivative equal to zero gives

$$\dot{TC}_{V^{RAIL,k}}^{RAIL} = -UN\dot{R}EL_{V^{RAIL,k}}^{RAIL,k} - \sum_j \frac{\partial o_j^{RAIL,k}}{\partial V_j^{RAIL,k}} DIS\dot{C}OM_{V^{RAIL,k}}^{RAIL}$$

$$-SC\dot{H}ED_{V^{RAIL,k}}^{RAIL,k} - E\dot{X}T_{V^{RAIL,k}}^{RAIL,k} + F\dot{U}EL_{V^{RAIL,k}}^{RAIL,k}, \forall k. \quad (14)$$

From Equation (14), we see that, other things being equal, an increase in the number of train runs operated introduces six effects:

(i) an increase in the production cost of the rail operator, $\dot{TC}_{V^{RAIL,k}}^{RAIL}$. Operating more runs costs more because of the variable costs such as the drivers wage. Moreover, increasing the number of runs during the peak period implies also an increase in the rolling stock.

(ii) an increase in the unreliability cost supported by users, $UN\dot{R}EL_{V^{RAIL,k}}^{RAIL,k}$. When more trains run on the rail network, the average unreliability increases because the probability that a train encounters a problem and then delays all the other trains is higher.

(iii) a decrease in the discomfort cost supported by users, $\sum_j \frac{\partial o_j^{RAIL,k}}{\partial V_j^{RAIL,k}} DIS\dot{C}OM_{V^{RAIL,k}}^{RAIL}$. Mechanically, an increase in the number of train runs raises the supplied capacity, decreases the occupancy rate $o_j^{RAIL,k}$, and eventually reduces the discomfort experienced by passengers.

(iv) a decrease in the schedule delay cost supported by users, $SC\dot{H}ED_{V^{RAIL,k}}^{RAIL,k}$. The set of possible arrival times during period k raises with the frequency of service, which itself increases with the number of runs operated. Consequently, users incur, in average, lower schedule delays costs (see Equation (7)).

(v) an increase in the environmental and accidents externalities supported by all individuals, $E\dot{X}T_{V^{RAIL,k}}^{RAIL,k}$. The cost of rail negative externalities increases with the number of runs operated (see Equation (9)).

(vi) an increase in the fuel tax revenue collected by the government from rail, $F\dot{U}EL_{V^{RAIL,k}}^{RAIL,k}$. The operation of more runs implies an increase in the fuel consumption.

In optimum, the number of train runs operated is set such that the marginal social benefit (the sum of effects (iii), (iv) and (vi)) equals the marginal social cost (the sum of effects (i), (ii) and (v)).

Rearranging Equation (14) with respect to the number of runs operated gives the optimal number of train runs operated during period k

$$V^{RAIL,k} = \sqrt{\frac{\begin{array}{c}\sum_i \sum_j N_{i,j} \cdot x_{i,j}^{RAIL,k} \cdot \alpha_i \cdot \delta \cdot h^k \\ + \sum_i N_{i,A} \cdot x_{i,A}^{RAIL,k} \cdot \frac{\alpha_i \cdot \eta^{RAIL}}{s^{RAIL}} \cdot X_A^{RAIL,k} \cdot \overline{tt}_{AB}^{RAIL} \\ + \sum_i \left[\begin{array}{c} \left(N_{i,A} \cdot x_{i,A}^{RAIL,k} + N_{i,B} \cdot x_{i,B}^{RAIL,k} \right) \cdot \frac{\alpha_i \cdot \eta^{RAIL}}{s^{RAIL}} \cdot \\ \left(X_A^{RAIL,k} + X_B^{RAIL,k} \right) \cdot \overline{tt}_{BD}^{RAIL} \end{array} \right]\end{array}}{\begin{array}{c}\sum_i \sum_j N_{i,j} \cdot x_{i,j}^{RAIL,k} \cdot \alpha_i \cdot \theta^{RAIL} \cdot \frac{\overline{tt}_{AB}^{RAIL} + \overline{tt}_{BD}^{RAIL}}{h^k} \\ + \Vert_{k=P} \overline{tt}_{BD}^{RAIL} 2 \cdot \overline{tt}_{AD}^{RAIL} \cdot V^{RAIL,P} / h^P \cdot \mu_1^{RAIL} \\ + \mu_2^{RAIL} + \left[\upsilon^{RAIL} \cdot \left(p^{fuel} - \kappa^{fuel} \right) - \iota^{RAIL} \right] \cdot d_{AD}^{RAIL}\end{array}}}, \ \forall k. \qquad (15)$$

where $\Vert_{k=p} = 1$ if $k = P$ and 0 if $k = 0$.

The first line of the RHS of Equation (15) corresponds to the "pure" Mohring effect (Mohring, 1972) for rail transit: other things and costs being equal, the number of operated vehicles increases with square root of the demand due to economies of scale in schedule delay costs.

However, the overall effect of the demand on the number of runs operated is uncertain. On the one hand, an increase in the train patronage makes an increase in runs operated socially more profitable due to positive schedule delay (line 1 of RHS in (15)) and discomfort (lines 2 and 3) effects. These two effects push into increasing the number of train runs. On the other hand, the unreliability cost per user increases with the number of trains. This pushes into decreasing the number of runs (fourth term in (15)).

Adding more trains is costly in terms of equipment and operation costs. The cost of the rolling stock only affects the number of runs during the peak period (i.e. when$\|_{k=p}= 1$). Not surprisingly, when this cost increases, the number of runs during peak period should decrease.

The sixth (and last) line in RHS of Equation (15) gathers the negative effects of the operating cost and of the externalities and the positive effect of the rail fuel tax revenue on the number of runs operated.

3.2.2. Optimal road tolls

Differentiating $\mathcal{L}$ in Equation (12) with respect to the number of private cars (or travelers in private cars) on road, $x_{i,j}^{CAR,k}$, setting equal to zero and rearranging give the optimal road toll for private cars.

$$\tau_j^{CAR,k} = CO\dot{N}G_{V_j^{CAR,k}}^{CAR,k} + E\dot{X}T_{V_j^{CAR,k}}^{CAR,k} - F\dot{U}EL_{V_j^{CAR,k}}^{CAR,k}, \forall k, j, \tag{16}$$

where $CO\dot{N}G_{V_j^{CAR,k}}^{CAR,k}$ is the total marginal cost of congestion of car drivers with respect to $V_j^{CAR,k}$, $E\dot{X}T_{V_j^{CAR,k}}^{CAR,k}$ is the marginal variation of externalities due to a variation of $V_j^{CAR,k}$, and $F\dot{U}EL_{V_j^{CAR,k}}^{CAR,k}$ is the variation of fuel tax revenue due to an increase of $V_j^{CAR,k}$.

Other things being equal, Equation (16) shows that increasing the number of individual cars, $V_j^{CAR,k}$ has four main effects on social welfare:

(i) if $\tau_j^{CAR,k} > 0$, more road toll revenues are collected.

(ii) an increase in the travel time for car which use road segment jD during period k, $C\dot{O}NG_{V_j^{CAR,k}}^{CAR,k}$. More vehicles use the same road whose capacity is fixed, creating longer traffic jams and increasing travel times.

(iii) an increase in the other negative externalities produced by cars, $E\dot{X}T_{V_j^{CAR,k}}^{CAR,k}$.

(iv) an increase in the fuel tax revenue collected by the government, $\mathrm{F}F\dot{U}EL_{V_j^{CAR,k}}^{CAR,k}$.

The optimal road toll for cars described in Equation (16) ensures that the average private cost of car road use equals the marginal social cost of this use. The toll (effect (i)) compensates the negative externality produced by car drivers (effects (ii) and (iii)) minus the increase in fuel tax revenue (effect (vi)). From the government perspective, the LHS of (20) plus the increase in fuel tax revenue is the marginal benefit with respect to the number of trips, whereas the RHS of (16) minus the increase in fuel tax revenue is the marginal social cost of such an increase.

3.3. Second best optimum: only rail is optimally supplied and priced

In many countries, use of road or motorways is not taxed, or motorways are owned by private companies that have other toll setting principles. In these cases, road tolls are constrained and $\tau_j^{CAR,k}$ cannot be changed. These instruments are not available anymore and the external congestion costs of road use are not internalized.

The optimal second best fare for rail is then equal to: expression (13) + sum of price distortions over all other modes and all periods times $\chi_{k,rail}^{m,l}$ where $\chi_{k,rail}^{m,l}$ is the diversion ratio to another mode or period when the price of rails increases. It equals the increase in the number of trips of mode m in period l when there is one passenger less for rail in period k (see Small & Verhoef (2007)). The most important distortion is the unpriced road congestion (LHS < RHS of (20)).

3.4. Second best optimum with additional rail deficit constraint

When there is a constraint on the maximum deficit, the budget constraint will increase prices beyond marginal costs. The additional margins will be proportional to the inverse of the price elasticity and the cross price elasticities.

4. Data

The model is calibrated on two corridors: Bruges - Ghent - Brussels in Belgium and Grenoble - Bourgoin-Jailleu[7] - Lyon. Four categories of users are distinguished: active people with relatively high revenue ("active +" in what follows), active people with low revenue ("active - " in what follows), students and retired. Data have been collected for year 2017, and if 2017 data were not available, we too the most recent sources.[8]

Table 1 reports some of the technological and rail cost data that are identical for the two corridors. These data were taken from different railway sources, which are detailed in Appendix, as well as the entire dataset. The environmental and accident externalities are much larger for a train-km than for a car-km. Peak values of time are 1.4 times higher than off-peak values of time.

[Table 1 here]

Table 2 presents the main characteristics specific to each corridors. Again, entire dataset and complete sources are detailed in Appendix. There are several differences between the two corridors. First, there is a larger number of trips in the Brussels corridor than in the Lyon corridor, mainly due to the size of cities and to their attraction. Second, whereas the use of highways is free in Belgium, there are road tolls in France. Finally, we observe price differentiation in France but not in Belgium.

[7] The city of Bourgoin-Jailleu is referred as "Bourgoin" in what follows.
[8] A detailed description of data is available in the appendices.

[Table 2 here]

Price elasticities and diversion factors χ to other modes are presented to the Appendices.

5. Results for one country

5.1. First and second best prices for corridor to Brussels

Table 3 reports the baseline (current prices and frequencies) as well as the second best and the first best scenario. For each scenario, the peak and off-peak results are reported for two types of trips: the trip from Bruges to Gent (52km) and the follow up trip from Ghent to Brussels (40km). As the same train equipment is used for both trips, the frequency and train composition is the same for both trips. We also assume all passengers have Brussels as their final destination.

It is easier to start the analysis with the first best scenario. In this scenario, rail fares and frequencies as well as road charges are optimized. Consider now the morning peak from Bruges to Brussels. The rail fare from Bruges to Brussels (the full trip) equals 3.7 Euro in the peak. This is more one half higher than the current fare (2.5).[9] The optimal fare equals 1 Euro crowding costs from Bruges to Ghent plus 2.8 Euro crowding costs from Ghent to Brussels. As the same train equipment is used for both parts of the trip, the crowding costs for the first part of the trip are naturally lower. The optimal peak fare from Ghent to Brussels is 2.5 Euro and more or less equal to the crowding cost. While current prices are very close in peak and off-peak (2.5 and 2.1 Euro from Bruges to Brussels), the first best optimal fares are lower for the peak than for the off-peak because there is less crowding. Of course the crowding depends on the frequency. The optimal frequency in the peak (6.6 runs/hour) is clearly higher than the current frequency (4 runs/hour). The optimal off-peak frequency (2 runs/hour) is equal to the current frequency. The optimal frequency balances crowding and schedule delay (rigidity) advantages with lateness costs and rolling stock and operation costs. We see in Table 3 that

[9] The current fare is an average fare; the fare structure is complex.

rolling stock costs only count for the frequency in the peak period. The peak frequency constraints the rolling stock quantity because it is much higher than the off-peak frequency.

In the peak period (4h/day) there are 7921 pass/h while in the off-peak period (15h/day) there are 1899 pass/h. Comparing this with the frequencies peak and off-peak, we see that number of passengers per hour is six times higher in the peak than in the off-peak, but frequencies are only 3 times higher in the peak than in the off-peak. The reason is the scheduling delay cost. While frequencies are mainly motivated by avoiding too much crowding (84 per cent of the contribution of the peak rail frequency to the total marginal utility is due to crowding, and 66 per cent for the off-peak frequency contribution), off-peak frequencies are also significantly driven by schedule delay (34 per cent of the off-peak frequency contribution).

In the first best scenario, road tolls are introduced mainly for the Ghent to Brussels section (5.7 Euro/car trip). These are necessary to internalize the external congestion costs, which diminish by 3.4 per cent. The first best pricing scenario results in an increase of rail ridership in the peak of some 5 per cent (3.5 per cent from Bruges and 5.3 per cent from Ghent) and a decrease of car use by 5 to 8 per cent. The lower rail and higher car prices result in a very small overall decrease in the number of trips.

For the train operator, higher prices and higher peak frequencies result in higher total revenues (+18 per cent) and higher operating costs (+23 per cent) as well as higher rolling stock costs as more peak equipment is needed (+65 per cent). The result is a much smaller gross margin to cover fixed costs (-61 per cent).

For the government, the lower gross margin on rail operations and the loss of fuel taxes is more than compensated by the additional toll revenues.

The total welfare gain is small per passenger trip (0.22 Euro) but important when one considers the large numbers of trips. All four categories of agents loose with the reform, mainly because transport becomes more expensive.

In the second best scenario, road tolls cannot be introduced so that the rail prices have now an important role in decreasing road congestion by attracting car users to rail. Optimal prices are now much lower: 1.6 Euro resp 0.7 Euro for Bruges and Ghent to Brussels in peak. The main drivers of the rail prices are now also different. Take Ghent to Brussels: the crowding costs would justify a rail fare of 2.8 Euro/trip but the reduction of car congestion associated to this low fare is 2.1 Euro, resulting in a net fare of 0.7 Euro/ trip. The optimal frequencies in the second best scenario are the same as in the first best scenario. The reason is that frequencies are determined by comparing benefits of existing rail users with rail costs. As the volume of rail use is close to the first best volume, the optimal frequencies are also close.

The low rail fares have two effects on the number of trips. It increases the number of rail trips and decreases the number of car trips. The decrease in the number of peak car trips (-1.1 per cent for Ghent-Brussels) is more limited than in the case of a toll (-7.6 per cent). The increase in the number of rail peak trips (1146 for Ghent to Brussels) is larger than the decrease of car trips (-411) so that a lower rail fare attracts more passengers of which in the peak around 36 per cent were car trips in the past. The lower fares generate, in total more trips (+1 per cent).

As prices are even lower in the second best scenario than in the first best scenario, the rail revenues decrease. As costs are more or less identical to the first best scenario, the gross margin of the rail company decreases further. Overall the second best scenario does a good job in terms of efficiency: even when car tolls cannot be introduced, one achieves 72 per cent of the welfare gains that can be achieved in the first best. One is tempted to conclude that controlling rail prices is an almost perfect substitute for road pricing. According to our model, the answer is yes with three important qualifiers. First it only holds for cars in a corridor where there is a good rail connection, second lower rail fares attract new passengers that are for 50 per cent former car users, and third, in as far as a much higher subsidy for rail can be financed without additional inefficiencies. Our results are not very different from those of Basso and Silva (2014) where within a metropolitan area, heavily subsidized busses on bus lanes do more or less as good as road pricing. Parry and Small (2009) also find second best fares for metropolitan areas that are very low but they do not compute the First Best scenario.

[Table 3 here]

5.2. What are main determinants of the marginal cost?

Rail companies serve areas with very different characteristics and their prices are often under public scrutiny as there are large public subsidies. Table 4 analyses the effects on second best rail prices of individual factors like a doubling of the population, halving the road capacity, halving the VOT and imposing a road toll of 2 Euro. In all these scenarios, the peak and off-peak frequencies are kept fixed. In the two last scenarios, we double the frequency and halve the frequency.

[Table 4 here]

Doubling the population leads to a 300 per cent increase of the peak prices because with given frequencies, crowding externalities increase. This increase of the crowding externalities dominates the increased road congestion. Whenever road congestion becomes much worse (halving the road capacity), it becomes important to decrease rail prices in the peak and off-peak. Whenever VOT is much higher rail fares should go up as the crowding externalities increase. These findings are important for a national rail company. If road congestion is structurally more important in one part of the country, or population growth makes the rail and road transport system in one region more prone to crowding and congestion, rail prices should be systematically higher. Low income regions should be given lower rail prices and lower frequencies, not because they are poor but because their crowding costs are smaller.

Road tolls, even limited to 2 Euro/ trip allow to move rail prices closer to marginal social costs of rail use.

In the two final scenarios, we double and halve the frequencies and see how they affect the second best fares. Doubling the frequencies makes crowding almost disappear and peak and off-peak fares become very low. Halving the frequencies more than doubles the second best rail fare.

5.3. Role of rail budget constraint

First best pricing of rail and second best pricing in the presence of unpriced road congestion generates lower prices and higher frequencies in the peak. This implies a larger deficit or at least a smaller operating margin. For instance second best pricing with unpriced road congestion generated a margin that decreases from 14 893 Euro to -65 306 Euro (Table 5).

When the margin (or deficit) has to be at least as high in the reference case, it is interesting to re-analyze the second best prices with unpriced road congestion. In order to address this question, we calibrate the model with price differentiation in the baseline scenario as well. Active people often enjoy discounted rail fares because of employer transportation benefits schemes.

The result is on average much higher prices in the peak for Bruges to Brussels (3.8 instead of 2.5 in baseline) and somewhat higher prices for Ghent to Brussels (2.2 instead of 1.9). In the off-peak period, the average prices are usually lower than the baseline prices. This is expected as the marginal social cost is much lower in the off-peak. Another interesting feature of the budget constraint scenario is the price discrimination across user groups. As students and retired people have less flexibility in their transport mode choice and have a higher willingness to pay, they tend to pay the highest fares. Active passengers face less extra margins.

[Table 5 here]

The two types of second best optimal rail prices (with and without budget constraint) are compared in Figure 2 for Ghent to Brussels (the link with most parallel car congestion). We see that the budget constraint drives peak prices for students and retired people close to current rail prices. Also for the active that travel in the peak, prices will be much higher than in the baseline. The main reason is the high marginal cost of supplying peak capacity. For the off-peak period, optimal prices are higher than in the baseline.

We find that the imposition of the budget constraint reduces strongly the efficiency gains of the second best. The efficiency gain is now half of that of the first best. We see higher prices (4.5 instead of 3.7 to go from Bruges to Brussels in the peak) but only a slightly lower frequency (6.4 rather than 6.6 in the peak). This is due also to a change in the composition of the train use: the high VOT users (active) are less discouraged than the low VOT users to use the peak trains and this justifies that frequency stays more or less constant when a budget constraint is imposed.

[Figure 2 here]

6. Comparing current prices and optimal prices across countries

We compare prices for corridors in 2 countries. For each of these corridors defined in Table 2 we compute two second best scenario's. The first is a second best scenario where current car prices are taken as given. The second scenario includes in addition a budget constraint. The budget constraint makes sure that the margin of the railway company is the same as in the baseline.

We concentrate on the results for the French corridor Grenoble – Bourgoin –Lyon. The detailed results for baseline, second best without budget constraint and first best are presented in Table 6. The French corridor is interesting because it has already tolls (*péages*) implemented on the motorways that take the bulk of the car traffic on this corridor (resp. 6.7 and 3.5 Euro/trip). These motorway tolls are however not optimized as they are set to finance the motorway using administrative rules that allow cross-financing. Comparing these tolls with the optimized tolls in the First Best columns, we find that the present tolls (6.7 in peak and off-peak rather than 1.2 or 0) are too high for the Grenoble to Bourgoin part and too high for the off-peak car traffic close to Lyon (At present it is 3.5 in off-peak while ideally it should be 0).

Because the present motorway tolls are too high, the second best rail prices are actually higher than the first best prices. In order to take into account the overpriced car use, it becomes optimal to charge fares higher than the marginal social costs. This holds as well in the peak as in the off-peak. For Grenoble to Bourgoin where there are the largest inefficiencies in car pricing, the second best fares end up close to the baseline fares.

As there is also a decrease in patronage for rail in the off-peak, it is also important to decrease the frequency in the off-peak (0.8 rather than 1 in the baseline).

The gross margin of the rail company increases in the second best scenario by 50.6 per cent. The too high road tolls make that the second best rail fares have a difficult time to achieve the full welfare gain (0.06 Euro per trip rather than the 0.23 per trip).

[Table 6 here]

7. Conclusion

This paper has looked into the efficiency of rail pricing for a corridor in Belgium and in France. We can conclude on some of our research questions.

First we find that for countries without road tolls, like Belgium, second best pricing of rail implies lower rail fares and higher frequencies. Peak fares are lower than in the first best because the low fares and higher frequency can achieve a large part of the efficiency gains of the first best. When the second best fares cannot increase the rail deficit, a large part of the second best efficiency gains is lost. In a country with a high road toll, like France, second best pricing of rail means actually higher fares than in the first best. Imposing a budget constraint is then not really an issue. The welfare gain of the second best scenario is rather small because the large distortion on the road market can not be corrected.

Second, we find that the optimal rail fares are mainly driven by two factors: the external crowding costs and the under or overpricing of road use. This means that, within one country (and within one rail company), fares should be a function of road congestion in the corridor, total number of rail users as well as income of the rail users. This is rather different from a national rail fare in function of distance.

Third, the crowding discomfort depends strongly on the value of time of the passenger. This means that passengers with a high aversion to crowding are prepared to pay extra when they can be sure to have a seat and travel in comfortable conditions. This means the distinction between First and Second class wagons and tickets can be welfare increasing.

Fourth, present and optimal railway fares vary strongly over countries.

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Figures

Figure 1: A simple network with two origins (A and B) and one destination (D)

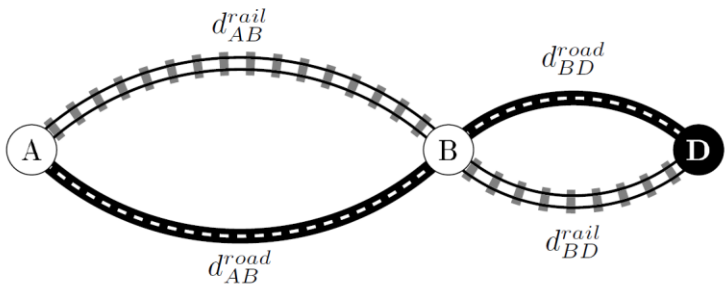
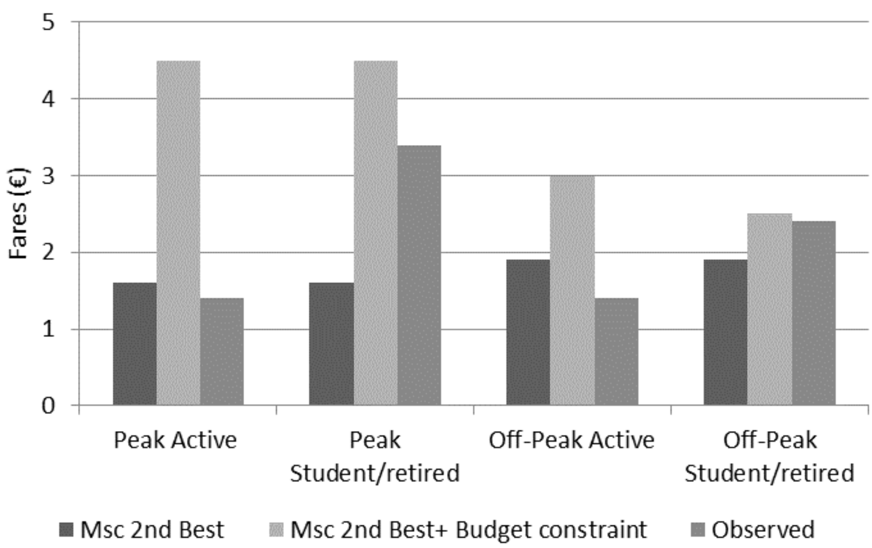


Figure 2: Prices for a rail trip from Bruges to Brussels (Belgium)



Tables

Parameters	Value	
Train environmental + accident externalities (€/km)	4.16	
Car environmental + accident externalities (€/km)	0.012	
Rail crowding cost (hours/users/m²)	0.16	
Rail scheduling cost (hours/runs/hour)	0.24	
Rail delay cost (hours x runs/hour)	0.22	
Values of time	Peak	Off-peak
Active +	17.7	12.6
Active -	14	10
Students	14	10
Retired	9.5	6.8

Table 1: Parameters whose value is the same for the two corridors

		Belgium	France
City A		Bruges	Grenoble
City B		Ghent	Bourgoin
City D		Brussels	Lyon
Number of daily trips			
	From A	40 000	20 000
	From B	110 000	20 000
Road tolls (€)			
A → D		0	6.7
B → D		0	3.5
Train fares (€)			
Peak	A → D	2.5	5.0
	B → D	1.9	2.3
Off-peak	A → D	2.1	7.5
	B → D	1.9	3.3
Rail frequency (train/hour)			
Peak		4	2
Off-peak		2	1

Table 2: Parameters whose value is corridor-specific

		Baseline		Second-best opt.		First-best opt.	
		Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Rail fares (€ per trip)							
From Bruges to Brussels		2.5	2.1	1.6	1.9	3.7	2.3
Amount of optimal fare due to:							
Crowding	*Bg → G*			*1*	*0.3*	*1*	*0.3*
	G → Bl			*2.8*	*1.3*	*2.8*	*1.3*
Substitution with other modes				*-2.1*	*0.3*	*0*	*0.7*
From Ghent to Brussels		1.9	1.9	0.7	1	2.5	1.4
Amount of optimal fare due to:							
Crowding	*G → Bl*			*2.8*	*1.3*	*2.8*	*1.3*
Substitution with other modes				*-2.1*	*-0.3*	*-0.3*	*-0.1*
Rail frequency (runs/hour)		4	2	6.6	2	6.6	2
Contribution to marginal utility:							
Crowding	*Bg → G*			*1 634*	*4 907*	*1 362*	*4 913*
	G → Bl			*13 341*	*17 846*	*13 288*	*17 897*
Rigidity of service				*2 716*	*11 915*	*2 709*	*11 924*
Contribution to marginal cost:							
Average lateness				*18 329*	*2 238*	*18 283*	*3 441*
Operating costs				*6 808*	*25 530*	*6 808*	*25 530*
Fuel consumption				*472*	*1 769*	*472*	*1 769*
Rolling stock cost				*4 406*	-	*4 406*	-
Environmental + accident externalities				*1 530*	*5 737*	*1 530*	*5 737*
Road tolls (€/trip)							
From Bruges to Brussels		0	0	0	0	1	0
Amount of optimal toll + fuel tax due to:							
Congestion						*1.6*	*0.1*
Environmental + accident externalities						*0.5*	*0.2*
Other effects						*0.2*	*0.4*
From Ghent to Brussels		0	0	0	0	5.7	0
Amount of optimal toll + fuel tax due to:							
Congestion						*7*	*0.6*
Environmental + accident externalities						*0.6*	*0.5*
Other effects						*0*	*0.4*
Demand (trips per day)				(variations w.r.t. baseline)			
from Bruges	Rail	9 029	8 156	3.6%	0.1%	3.5%	0.1%
	Car	12 337	10 502	-0.8%	-0.5%	-5.3%	1.2%
from Ghent	Rail	21 215	19 322	5.4%	5.2%	5.3%	5.2%
	Car	37 358	32 074	-1.1%	-2.3%	-7.6%	0.2%
Labour supply		82 146		0.2%		-1.1%	
Individual costs (minutes per trip)							
Rail crowding	*Bg → G*	6.4	3.1	-37.2%	0.1%	-37.3%	0.1%
	G → Bl	16.6	8.1	-36.4%	3.7%	-36.4%	3.7%
Rail scheduling cost		3.5	7.1	-39.4%	0.0%	-39.4%	0.0%
Rail lateness		1.3	0.7	65.0%	0.0%	65.0%	0.0%
Road congestion	*Bg → G*	7.4	1.7	-0.8%	-0.5%	-5.3%	1.2%
	G → Bl	30	6.9	-1.1%	-1.9%	-7.0%	0.4%
Aggregates (€ per day)							
Train company				(variations w.r.t. baseline)			
Turnover (net of private or public subsidies)		116 267		-42.8%		18.4%	
Operating cost		83 749		22.6%		22.6%	
Rolling stock cost		17 624		65.0%		65.0%	
Margin		14 893		-538.5%		-60.6%	
Government							
Toll revenues		0		0		275 095	
Fuel tax revenues		226 071		-1.3%		-3.3%	
Environmental + accident externalities							
Rail		17 593		22.6%		22.6%	
Road		75 299		-1.3%		-3.4%	
Net surplus per user (€ per day)				(variations w.r.t. baseline)			
		Bruges	Ghent	Bruges	Ghent	Bruges	Ghent
Active +		116.5	99.3	0.3%	0.3%	-0.9%	-1.4%
Active -		99.3	90.2	0.3%	0.4%	-0.9%	-1.2%
Students		56	51	0.9%	1.3%	-0.5%	-0.7%
Retired		77.5	75.7	0.2%	0.4%	-0.4%	-0.4%
Total welfare gain (€ per day)		-		24 246		33 636	
Efficiceny (%)		-		12.1%		100%	
Welfare gain per baseline trips (€/trip)		-		0.16		0.22	

Table 3: Baseline. optimal rail fares and frequency. and first-best optimum estimates for trips from Bruges and Ghent to Brussels (Belgium).

		Second-best optimum	Alternatives scenarios					
			Population x 2	Road capacity / 2	VoT x 2	Roas dtolls = 2€	Frequencies x 2	Frequences / 2
Peak	Bruges → Brussels	1.6	5.9	0.9	5.9	4.3	0.9	8.4
	Ghent → Brussels	0.7	3.4	0	3.4	3.1	0.2	5.6
Off-peak	Bruges → Brussels	1.9	2.5	0.9	2.3	2.9	1.1	3.4
	Ghent → Brussels	1	1.3	0.2	1.1	1.1	0.4	2

Table 4: Optimal Second Best rail fares with baseline rail frequencies under alternative scenarios

	Baseline		Optimal rail fares		Optimal rails fares + freq.	
	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Average rail fares (€ per trip)						
From Bruges to Brussels	2.5	2.1	3.8	2	4.5	2.7
From Ghent to Brussels	1.9	1.9	2.2	1	2.4	1.5
Detailed rail fares (€ per trip)						
Active + and Active -						
From Bruges to Brussels	1.4	1.4	3	2	4.5	3.
From Ghent to Brussels	1.1	1.1	1	1	1.5	1.5
Students and Retired						
From Bruges to Brussels	3.4	2.4	4.5	2	4.5	2.5
From Ghent to Brussels	2.4	2.2	3	1	3	1.5
Rail frequency (runs/hour)	4	2	4	2	6.4	2
Rail company margin (€)	14 893		15 490		14 235	
Total welfare gain (€ per day)	-		790		18 214	
Welfare gain per baseline trips (€ per trip)	-		0.01		0.12	

Table 5: Baseline (0). optimal rail fares with baseline frequency (1) and optimal rail fares and optimal frequency (2) with budget constraint and price discrimination for trips from Bruges and Ghent to Brussels (Belgium)

		Baseline		Second-best opt.		First-best opt.	
		Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Rail fares (€ per trip)							
From Grenoble to Lyon		5	7.5	7.1	7.6	4	2.3
Amount of optimal fare due to:							
Crowding	*G → B*			*1.9*	*0.6*	*1.9*	*0.6*
	B → L			*1..8*	*0.7*	*1.8*	*0.7*
Substitution with other modes				*3.4*	*6.3*	*0.3*	*1.0*
From Bourgoin to Lyon		2.3	3.3	2.5	2.6	1.8	0.9
Amount of optimal fare due to:							
Crowding	*B → L*			*1.8*	*0.7*	*1.8*	*0.7*
Substitution with other modes				*0.7*	*1.9*	*0*	*0.2*
Rail frequency (runs/hour)		2	1	2.3	0.8	2.3	0.8
Contribution to marginal utility:							
Crowding	*G → B*			*3 729*	*5 777*	*3 718*	*5 806*
	B → L			*6 601*	*6 468*	*6 581*	*6 455*
Rigidity of service				*5 654*	*11 633*	*5 640*	*11 593*
Contribution to marginal cost:							
Average lateness				*1 615*	*140*	*1 611*	*139*
Operating costs				*7 384*	*27 690*	*7 384*	*27 690*
Fuel consumption				*626*	*2 349*	*626*	*2 349*
Rolling stock cost				*4 957*	*0*	*4 957*	*0*
Environmental + accident externalities				*2 162*	*8 106*	*2 162*	*8 106*
Road tolls (€/trip)							
From Grenoble to Lyon		6.7	6.7	6.7	6.7	1.2	0
Amount of optimal toll + fuel tax due to:							
Congestion						*2.1*	*0.1*
Environmental + accident externalities						*0.7*	*0.3*
Other effects						*0.3*	*0.6*
From Bourgoin to Lyon		3.5	3.5	3.5	3.5	3.9	0
Amount of optimal toll + fuel tax due to:							
Congestion						*4.8*	*0.4*
Environmental + accident externalities						*0.5*	*0.4*
Other effects						*0*	*0.3*
Demand (trips per day)				(variations w.r.t. baseline)			
from Grenoble	Rail	4 516	4 039	-1.4%	-2.3%	-1.4%	-2.3%
	Car	6 170	5 275	0.4%	1.0%	1.5%	15.7%
from Bourgoin	Rail	3 845	3 639	2.1%	-11%	2.1%	-10.9%
	Car	6 783	5 771	0.1%	2.8%	-0.9%	17.6%
Labour supply		22 025		-0.1%		3.7%	
Individual costs (minutes per trip)							
Rail crowding	*G → B*	9.4	4.5	-14.2%	22.1%	-14.3%	22.1%
	B → L	8.3	4.1	-13.4%	23.5%	-13.5%	23.6%
Rail scheduling cost		7.1	14.2	-13%	25%	-13%	25%
Rail lateness		0.7	0.3	15%	-20%	15%	-20%
Road congestion	*G → B*	9.3	2.1	0.4%	1%	1.5%	15.7%
	B → L	19.4	4.4	0.1%	0.4%	-0.5%	15.3%
Aggregates (€ per day)							
Train company				(variations w.r.t. baseline)			
Turnover (net of private or public subsidies)		73 819		9.4%		9.4%	
Operating cost		46 059		-7.8%		-7.8%	
Rolling stock cost		9 914		15%		15%	
Margin		17 846		50.6%		50.6%	
Government							
Toll revenues		160 677		0.5%		-64%	
Fuel tax revenues		62 691		0.4%		7.3%	
Environmental + accident externalities							
Rail		12 430		-7.8%		-7.8%	
Road		20 954		0.4%		7.3%	
Net surplus per user (€ per day)				(variations w.r.t. baseline)			
		Grenoble	Bourgoin	Grenoble	Bourgoin	Grenoble	Bourgoin
Active +		71.1	83.9	0%	0%	0.3%	0.6%
Active -		54.4	70.8	0%	0%	0.3%	0.6%
Students		35.5	42.9	-0.1%	0.1%	0.3%	0.9%
Retired		61.9	69.6	0%	0%	0.3%	0.9%
Total welfare gain (€ per day)		-		2 253		9 203	
Efficiceny (%)		-		24.51%		100%	
Welfare gain per baseline trips (€/trip)		-		0.06		0.23	

Table 6: Baseline, optimal rail fares and frequency, and first-best optimum estimates for trips from Grenoble and Bourgoin to Lyon (France).

Appendices

A. Detailed data

The specification of the gross utility function defined in Eq. (1) used in the empirical exercise in Sections 5 and 6 is:

$$
\begin{aligned}
U_{i,,j} = \quad & q_{i,j} + [a_{i,j}^{CAR,P} x_{i,j}^{CAR,P} - 0.5 b_{i,j}^{CAR,P} (x_{i,j}^{CAR,P})^2] \\
& + [a_{i,j}^{CAR,OP} x_{i,j}^{CAR,OP} - 0.5 b_{i,j}^{CAR,OP} (x_{i,j}^{CAR,OP})^2] \\
& + [a_{i,j}^{RAIL,P} x_{i,j}^{RAIL,P} - 0.5 b_{i,j}^{RAIL,P} (x_{i,j}^{CAR,P})^2] \\
& + [a_{i,j}^{RAIL,OP} x_{i,j}^{RAIL,OP} - 0.5 b_{i,j}^{RAIL,OP} (x_{i,j}^{RAIL,OP})^2] \\
& - e_{i,j}^{CAR,P/CAR,OP} x_{i,j}^{CAR,P} x_{i,j}^{CAR,OP} - e_{i,j}^{CAR,P/RAIL,P} x_{i,j}^{CAR,P} x_{i,j}^{RAIL,P} \\
& - e_{i,j}^{CAR,P/RAIL,OP} x_{i,j}^{CAR,P} x_{i,j}^{RAIL,OP} - e_{i,j}^{CAR,OP/RAIL,P} x_{i,j}^{CAR,OP} x_{i,j}^{RAIL,P} \\
& - e_{i,j}^{CAR,OP/RAIL,OP} x_{i,j}^{CAR,OP} x_{i,j}^{RAIL,OP} - e_{i,j}^{RAIL,P/RAIL,OP} x_{i,j}^{RAIL,P} x_{i,j}^{RAIL,OP}.
\end{aligned}
$$

are parameters to be calibrated. This is the same specification as in in Börjesson, et al. (2017).

Data have been collected for year 2012. When data were not available for this year, we chose data whose publication date is close to this year.

Table 7 reports technological and rail cost data which are identical for the two corridors. Peak period is four hours long, two hours during the morning peak (7am to 9am) and two hours during evening peak (5pm to 7pm). The total (fixed + variable) cost of a train has been computed by considering a cost of 10M euros per carriage, a lifespan of 30 years, a discount rate of 4 per cent and 350 days of use per year. The total cost is equally split between fixed cost and variable cost in the baseline. The variable cost takes the form of a cost per seat per train. We assume a train operating cost of 12 euros per km, based on the Belgium data in Steer Davis Gleave (2015). The train fuel consumption is kept voluntarily low because in Belgium and France a non-negligible part of the lines are electrified. The environmental and accident externalities for train and car have been found in the Update of the Handbook of External Costs of Transport.[10] The car fuel consumption corresponds to an average consumption of 7 liters per km.

The rail crowding cost coefficient has been obtained by a linear approximation of the travel time multipliers estimated by Kroes, et al. (2013). The scheduling cost coefficient has been computed in the $\alpha - \beta - \gamma$ framework by using the estimations produced by Wardman, et al. (2012). The rail delay cost efficient we use is from Pérez Herrero, et al. (2014).

The off-peak values of time are officially recommended values used in France (Quinet, 2013). The peak values of time have been obtained by using a factor 1.4 (Abrantes & Wardman, 2011).

Parameters	Value	
Peak period length (hours)	4	
Off-peak period length (hours)	15	
Cost of train (€/train/day)	1 650	
Train operating cost (€/km)	12	
Train fuel consumption (l/km)	1	
Train environmental + accident externalities (€ /km)	4.16	
Car fuel consumption (l/km)	0.07	
Car environmental + accident externalities (€ /km)	0.012	
Rail crowding cost (hours/users/m²)	0.16	
Rail scheduling cost (hours/runs/hour)	0.24	
Rail delay cost (hours \times runs/hour)	0.22	
Values of time (€ /hour)	Peak	Off-peak
Active +	17.6	12.6
Active -	14	10
Students	14	10
Retired	9.5	6.8

Table 7: Parameters whose value is the same for all cases

We assume that the four categories are uniformly represented among the population of each of the city. Table 8 gives the modal shares per period distribution for the 4 types of users in the initial equilibrium. These numbers have been inferred from different sources (Cornelis, et al.

[10] https://ec.europa.eu/transport/sites/transport/files/handbook_on_external_costs_of_transport_2014_0.pdf

(2012); Auvergne-Rhône-Alpes (2014); Duabresse et al. (2015); AURG and SMTC (2015); Andries (2016)).

		Active +	Active -	Students	Retired	Total
Distribution trips from A						
Train	Peak	5.6%	4.6%	9.3%	3.1%	22.6%
	Off-peak	3.7%	3.1%	6.2%	7.2%	20.2%
Car	Peak	13%	10.2%	4.2%	3.5%	30.9%
	Off-peak	8.7%	6.8%	2.8%	8.1%	26.4%
Total		30.9%	24.7%	22.4%	21.9%	100%
Distribution trips from B						
Train	Peak	3.5%	4.3%	8.6%	2.9%	19.3%
	Off-peak	2.3%	2.9%	5.8%	6.7%	17.6%
Car	Peak	13.8%	11.1%	5.2%	3.9%	34%
	Off-peak	9.2%	7.4%	3.5%	9.1%	29.1%
Total		28.8%	25.7%	23%	22.5%	100%

Table 8: Trips characteristics

Table 9 presents the geographical and physical characteristics of the two corridors. The road distance between cities as well as the road free travel times have been obtained through website Google Maps. The rail distances between cities have been retrieved from Wikipedia pages dedicated to the railway stations.[11] [12] [13] The rail average speeds have been retrieved from the timetables. The road congestion cost coefficient has been calibrated such that it reproduces the observed travel time while using a linear congestion function.

[11] https://fr.wikipedia.org/wiki/Ligne_50A_(Infrabel)
[12] https://fr.wikipedia.org/wiki/Gare_de_Bourgoin-Jallieu
[13] https://fr.wikipedia.org/wiki/Gare_de_Grenoble

	Belgium	France
City A	Bruges	Grenoble
City B	Ghent	Bourgoin
City D	Brussels	Lyon
Population living in A	100 000	700 000
Population living in B	200 000	60 000
Number of daily trips		
From A	40 000	20 000
From B	110 000	20 000
Distance AB rail (km)	52	88
Distance BD rail (km)	40	42
Distance AB road (km)	44	50
Distance BD road (km)	56	64
Average free train speed (km/hour)	69	87
Average free car speed (km/hour)	78	92
Road congestion cost (hours /veh/road capacity)	0.2	0.6

Table 9: General parameters whose value is corridor specific

Table 10 displays detailed transport data which are corridor specific. Comparable rail access (or infrastructure) charges for Belgium and France have been found in Thompson (2008). These data are less recent than the others, but this source assures comparability. Train capacities (number of seats per train) and frequencies have been computed from the description of the rolling stocks used on each of the lines and on the supplied service. [14] [15] Different materials are used, so these figures have to be interpreted as average. Trains in Belgium are slightly larger than in France. Road capacity per hour corresponds to three lanes highway. Fuel prices and excises have been compiled from the Europe's Energy Portal.[16] As there is no the same proportion of diesel and unleaded vehicles in both countries, we weighted prices and excise with respect to the shares of the vehicle types per country given by the European Automobile Manufacturers Association.[17]

[14] https://fr.wikipedia.org/wiki/InterCity_(Belgique)
[15] https://fr.wikipedia.org/wiki/Ligne_Lyon_-_Grenoble
[16] https://www.energy.eu/fuelprices/
[17] http://www.acea.be/statistics/tag/category/passenger-car-fleet-by-fuel-type

Road tolls for France have been retrieved from a local newspaper article.[18] We met difficulties in estimating the average fare paid by train users: some users buy an annual or season ticket, some others pay full price for a one way trip... Consequently, we chose to retain the price of an annual ticket.[19] [20] This price is spread on 250 working days and 2 trips a day. As the annual ticket is usually the cheapest one, we apply on it a multiplicative coefficient of two.

		Belgium	France
Rail access charges (€ /km)		6.5	2.2
Train capacity (seats/train)		650	600
Rail frequency (train/hour)			
Peak		4	2
Off-peak		2	1
Road capacity (veh/hour)			
	A → B	6 000	6 000
	B → D	6 000	6 000
Fuel price[21] (€ /l)		1.28	1.2
Fuel excise (€ /l)		0.51	0.52
Road tolls (€)			
	A → B	0	6.7
	B → D	0	3.5
Train fares (€)			
Peak	A → B	2.5	5.0
	B → D	1.9	2.3
Off-peak	A → B	2.1	7.5
	B → D	1.9	3.3

Table 10: Transport parameters whose value is corridor specific

B. Elasticities and cross elasticities

Tables 11, 12, 13 and 14 present the price elasticities and diversion factors χ to other modes and this for the 4 categories of users. These data are consistent with the literature (Mayeres (2000); Litman (2004); Oum, et al. (2008); Dargay and Clark (2012)). In the absence of more

[18] http://www.ledauphine.com/isere-nord/2012/01/31/si-vous-entrez-a-villefontaine
[19] http://www.belgianrail.be/en/tickets-railcards/age/adults-seniors/frequent/section-season-ticket.aspx
[20] https://www.ter.sncf.com/auvergne-rhone-alpes/tarifs/devis/recherche?oldRegion=RAL
[21] Includes VAT and excise.

locally differentiated data, we use for the two corridors the same demand and price elasticity data. This makes the corridors more comparable but also loses some realism.

Active +		Peak		Off-peak	
		Rail	Car	Rail	Car
Elasticities					
Elasticity of demand wrt generalized cost		-0.3	-0.3	-0.6	-0.6
Fraction of increased transit coming from					
Peak	Rail	-	End.	End.	End.
	Car	0.5	-	End.	End.
Off-peak	Rail	0.15	0.15	-	End.
	Car	0.15	0.15	0.5	-
Increased overall travel demand		End.	End.	End.	End.

Note: “End.” means that the number is endogenously determined.

Table 11: Cost-elasticities and origins of increased transit of the representative individual of the active + population

Active -		Peak		Off-peak	
		Rail	Car	Rail	Car
Elasticities					
Elasticity of demand wrt generalized cost		-0.2	-0.2	-0.6	-0.6
Fraction of increased transit coming from					
Peak	Rail	-	End.	End.	End.
	Car	0.7	-	End.	End.
Off-peak	Rail	0.05	0.05	-	End.
	Car	0.05	0.05	0.7	-
Increased overall travel demand		End.	End.	End.	End.

Note: “End.” means that the number is endogenously determined.

Table 12: Cost-elasticities and origins of increased transit of the representative individual of the active – population

Students		Peak		Off-peak	
		Rail	Car	Rail	Car
Elasticities					
Elasticity of demand wrt generalized cost		-0.3	-0.3	-0.7	-0.7
Fraction of increased transit coming from					
Peak	Rail	-	End.	End.	End.
	Car	0.2	-	End.	End.
Off-peak	Rail	0.1	0.1	-	End.
	Car	0.1	0.1	0.3	-
Increased overall travel demand		End.	End.	End.	End.

Note: “End.” means that the number is endogenously determined.

Table 13: Cost-elasticities and origins of increased transit of the representative individual of the students population

Retired		Peak		Off-peak	
		Rail	Car	Rail	Car
Elasticities					
Elasticity of demand wrt generalized cost		-0.5	-0.5	-0.7	-0.7
Fraction of increased transit coming from					
Peak	Rail	-	End.	End.	End.
	Car	0.2	-	End.	End.
Off-peak	Rail	0.3	0.3	-	End.
	Car	0.3	0.3	0.6	-
Increased overall travel demand		End.	End.	End.	End.

Note: “End.” means that the number is endogenously determined.

Table 14: Cost-elasticities and origins of increased transit of the representative individual of the retired population

C. First-best optimum

a. Objective function

The Lagrangian function is as follows

$$\mathcal{L} = \sum_i \sum_j N_{i,j} \times \left[\underbrace{U_{i,j}}_{\text{Users srplus}} + \underbrace{\sum_m \sum_k x_{i,j}^{m,k} \times NMUC_{i,j}^{m,k}}_{Users\ non-monetary\ costs} \right]$$

$$+ \underbrace{\Pi^{RAIL}}_{\text{Rail company profit}} - \underbrace{\sum_m \sum_k EXT^{m,k}}_{Pollution\ and\ accident\ externalities}$$

$$+ \underbrace{\kappa^{fuel} \times \left[(V^{RAIL,P} + V^{RAIL,OP}) \times v^{RAIL} \times d_{AD}^{rail} + \sum_k \sum_j V_j^{CAR,k} \times v^{CAR} \times d_{jD}^{road} \right]}_{\text{Revenue of the fuel tax}}$$

$$+ \underbrace{\sum_k \sum_j V_j^{CAR,k} \times \tau_j^{CAR,k}}_{\text{Revenue of the road tolls}}$$

$$+ \underbrace{\sum_i \sum_j \lambda_{i,j} \times \left(R_{i,j} - q_{i,j} - \sum_m \sum_k x_{i,j}^{m,k} \times MUC_j^{m,k} \right)}_{\text{Revenue of the road tolls}}$$

We derive $\mathcal{L}$ with respect to $\lambda_{i,j}$:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \lambda_{i,j}} &= R_{i,j} - q_{i,j} - \sum_m \sum_k MUC_j^{m,k} x_{i,j}^{m,k} \\ \Leftrightarrow q_{i,j} &= R_{i,j} - \sum_m \sum_k MUC_j^{m,k} x_{i,j}^{m,k} \end{aligned}$$

The revenue is fully spent.

b. Optimal quantity of the numeraire good consumed

Optimal quantities of the numeraire goods is given by:

$$\frac{\partial \mathcal{L}}{\partial q_{i,j}} = N_{i,j}\frac{\partial U_{i,j}}{\partial q_{i,j}} - \lambda_{i,j}.$$

Recalling that $\frac{\partial U_{i,j}}{\partial q_{i,j}} = 1$, it implies

$$\lambda_{i,j} = N_{i,j}. \qquad \text{(App. 1)}$$

c. Optimal train fares

To find the optimal level of train fares, we derive $\mathcal{L}$ with respect to $x_{i,j}^{RAIL,k}$.

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial x_{i,B}^{RAIL,k}} = {} & N_{i,B}\left(\frac{\partial U_{i,B}}{\partial x_{i,B}^{RAIL,k}} - NMUC_{i,B}^{RAIL,k}\right) \\ & -\sum_{n}\sum_{r} N_{n,r}\cdot x_{n,r}^{RAILk}\cdot\left[\frac{\partial X_B^{RAIL,k}}{\partial x_{i,B}^{RAIL,k}}\frac{\partial o_B^{RAIL,k}}{\partial X_B^{RAIL,k}}\cdot\frac{\partial discom_{n,B}^{RAIL,k}}{\partial o_B^{RAIL,k}}\right] \\ & +p_B^{RAIL,k}\frac{\partial X_B^{RAIL,k}}{\partial x_{i,B}^{RAIL,k}} - \lambda_{i,B}MUC_B^{RAIL,k}\end{aligned}$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial x_{i,A}^{RAIL,k}} = {} & N_{i,A}\left(\frac{\partial U_{i,A}}{\partial x_{i,A}^{RAIL,k}} - NMUC_{i,A}^{RAIL,k}\right) \\ & -\sum_{n}\sum_{r} N_{n,r}\cdot x_{n,r}^{RAIL,k}\cdot\left[\begin{array}{c}\frac{\partial X_A^{RAIL,k}}{\partial x_{i,A}^{RAIL,k}}\frac{\partial o_{AB}^{RAIL,k}}{\partial X_A^{RAIL,k}}\cdot\frac{\partial discom_{n,A}^{RAIL,k}}{\partial o_A^{RAIL,k}} \\ +\frac{\partial X_B^{RAIL,k}}{\partial x_{i,A}^{RAIL,k}}\frac{\partial o_B^{RAIL,k}}{\partial X_B^{RAIL,k}}\cdot\frac{\partial discom_{n,B}^{RAIL,k}}{\partial o_B^{RAIL,k}}\end{array}\right] \\ & +p_A^{RAIL,k}\frac{\partial X_A^{RAIL,k}}{\partial x_{i,A}^{RAIL,k}} - \lambda_{i,A}MUC_A^{RAIL,k}\end{aligned}$$

Recall that $\lambda_{i,j} = N_{i,j}$ from Equation (App. 1), that $MUC_j^{RAIL,k} = p_j^{RAIL,k}$, that $\frac{\partial U_{i,j}}{\partial x_{i,j}^{RAIL,k}} - NMUC_{i,j}^{RAIL,k} = MUC_{i,j}^{RAIL,k}$ from Equation (11) and that $\frac{\partial X_j^{RAIL,k}}{\partial x_{i,j}^{RAIL,k}} = N_{i,j}^{RAIL,k}$. Setting Equations above equal to zero and rearranging, we find the optimal fares of a journey by train

$$p_B^{RAIL,k} = \sum_n \sum_r N_{n,r} \cdot x_{n,r}^{RAIL,k} \cdot [\frac{\partial o_B^{RAIL,k}}{\partial X_B^{RAIL,k}} \cdot \frac{\partial discom_{n,B}^{RAIL,k}}{\partial o_B^{RAIL,k}}];$$

$$p_A^{RAIL,k} = \sum_n \sum_r N_{n,r} \cdot x_{n,r}^{RAIL,k} \cdot [\frac{\partial o_A^{RAIL,k}}{\partial X_A^{RAIL,k}} \cdot \frac{\partial discom_{n,A}^{RAIL,k}}{\partial o_A^{RAIL,k}} + \frac{\partial o_B^{RAIL,k}}{\partial X_A^{RAIL,k}} \cdot \frac{\partial discom_{n,B}^{RAIL,k}}{\partial o_B^{RAIL,k}}].$$

This can be simply rewritten as

$$p_j^{RAIL,k} = \frac{\partial o_j^{RAIL,k}}{\partial X_j^{RAIL,k}} \dot{DISCOM}_{o_j^{m,k}}^{RAIL,k}, \qquad \forall k, j,$$

where $\dot{DISCOM}_{o_j^{m,k}}^{RAIL,k}$ is the variation in aggregated discomfort cost in rail during period k due to a change in the occupancy rate from j to D during period k.

d. Optimal train supply

To find the optimal train supply, we derive $\mathcal{L}$ with respect to the number of runs operated, $V^{RAIL,k}$, and to the optimal number of seats per train, S^{RAIL}.

$$\frac{\partial \mathcal{L}}{\partial V^{RAIL,k}} = -\sum_i \sum_j N_{i,j} \cdot x_{i,j}^{RAIL,k} \cdot \left(\frac{\partial unrel_i^{RAIL,k}}{\partial V^{RAIL,k}} + \frac{\partial o_A^{RAIL,k}}{\partial V^{RAIL,k}} \frac{\partial discom_{i,j}^{RAIL,k}}{\partial o_A^{RAIL,k}} + \frac{\partial o_B^{RAIL,k}}{\partial V^{RAIL,k}} \frac{\partial discom_{i,j}^{RAIL,k}}{\partial o_B^{RAIL,k}} + \frac{\partial sched_i^{RAIL,k}}{\partial V^{RAIL,k}} \right) - \frac{\partial TC^{RAIL}}{\partial V^{RAIL,k}} - \frac{\partial EXT^{RAIL,k}}{\partial V^{RAIL,k}} + \kappa^{fuel} \times \upsilon^{RAIL} \times d_{AD}^{rail},$$

$$\frac{\partial \mathcal{L}}{\partial S^{RAIL}} = -\sum_i \sum_j N_{i,j} \cdot \sum_k x_{i,j}^{RAIL,k} \left(\frac{\partial o_A^{RAIL,k}}{\partial S^{RAIL}} \frac{\partial discom_{i,j}^{RAIL,k}}{\partial o_A^{RAIL,k}} + \frac{\partial o_B^{RAIL,k}}{\partial S^{RAIL}} \frac{\partial discom_{i,j}^{RAIL,k}}{\partial o_B^{RAIL,k}} \right) - \frac{\partial TC^{RAIL}}{\partial S^{RAIL}}.$$

Setting Equations above equal to zero and rearranging, we find

$$\dot{TC}^{RAIL}_{V^{RAIL,k}} = -\dot{UNREL}^{RAIL,k}_{V^{RAIL,k}} - \sum_j \frac{\partial o_j^{RAIL,k}}{\partial V^{RAIL,k}} \dot{DISCOM}^{RAIL,k}_{o_j^{RAIL,k}} - \dot{SCHED}^{RAIL,k}_{V^{RAIL,k}}$$
$$-\dot{EXT}^{RAIL,k}_{V^{RAIL,k}} + \dot{FUEL}^{RAIL}_{V^{RAIL,k}}, \forall k,$$
$$\dot{TC}^{RAIL}_{S^m} = -\sum_k \sum_j \frac{\partial o_j^{RAIL,k}}{\partial S^{RAIL}} \dot{DISCOM}^{RAIL,k}_{o_j^{RAIL,k}}.$$

e. Optimal road tolls

To find the optimal level of travel quantities, we derive $\mathcal{L}$ with respect to $x_{i,j}^{CAR,k}$

$$\frac{\partial \mathcal{L}}{\partial x_{i,j}^{CAR,k}} = N_{i,j}\left(\frac{\partial U_{i,j}}{\partial x_{i,j}^{CAR,k}} - time_{i,j}^{CAR} - cong_{i,j}^{CAR,k}\right) - \sum_n \sum_r N_{n,r} \cdot x_{n,r}^{CAR,k} \cdot \frac{\partial cong_{n,r}^{CAR,k}}{\partial V_j^{CAR,k}}$$
$$-\frac{\partial EXT^{CAR,k}}{\partial V_j^{CAR,k}} + (\kappa^{gas} \times v^m \times d_{jD}^{road} + \tau_j^{CAR,k}) - \lambda_{i,j} MUC_j^{CAR,k}$$

Recall that $\lambda_{i,j} = N_{i,j}$ from Equation (App. 1), that $MUC_j^{CAR,k} = \kappa^{gas} + v^m \times d_{jD}^{road} + \tau_j^{Car,k}$, and that $\frac{\partial U_{i,j}}{\partial x_{i,j}^{CAR,k}} - NMUC_{i,j}^{CAR,k} = MUC_{i,j}^{CAR,k}$ from Equation (11)). Setting Equations above equal to zero and rearranging, we find the optimal tolls on road

$$\tau_j^{CAR,k} = \dot{CONG}^{CAR,k}_{V_j^{CAR,k}} + \dot{EXT}^{CAR,k}_{V_j^{CAR,k}} - \dot{FUEL}^{CAR}_{V_j^{CAR,k}}, \qquad \forall k, j.$$

Appendices references

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