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Abstract

This study estimates the impact of a carbon tax on welfare, considering modal shifts to less carbon-intensive transport, as well as its effects on environmental and fiscal externalities. We calibrate a modal competition model using logit demand functions for a specific long-distance connection in France and simulate the introduction of a Pigouvian tax. Our key findings are: First, a €190/tCO2 carbon tax is nearly welfare-neutral but significantly detrimental to consumer surplus; Second, rail price regulation has the side effect of reducing greenhouse gas emissions by subsidizing the cleanest transport mode; Third, the widespread adoption of electric vehicles enhances overall welfare without significantly harming consumer surplus.

JEL Codes: D43, L91, R40, Q51
Keywords: Modal competition, environmental externalities, carbon tax, high-speed rail.

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1. Introduction

The transport sector is one of the largest emitters of greenhouse gases in both Europe and the United States, accounting for approximatively 30 percent of total emissions. In France, they have continued to rise in recent years, accounting for almost 32 percent of total emissions by 2022. Several mechanisms are being considered by the public authorities to accelerate the ecological transition in this sector, through prices (carbon tax, ETS market), standards (up to and including the banning of cars in cities or new combustion-powered vehicles), as well as all measures in favor of investment (decarbonized transport, innovation, subsidies in favor of electric car). One of the main obstacles is political, insofar as the ecological transition comes at a cost for passengers - in the form of an increase in their transport bill or a renunciation to travel. It is important to carefully weight up the different effects of these policies - in particular, the introduction of a Pigouvian tax not only does not have an a priori systematically positive effect on welfare due to existing market distortions, but it can result in a very significant loss for users.

The aim of this work is to estimate the impact of a carbon tax on welfare considering modal shifts to less carbon-intensive transport (train, electric car) and the reduction of externalities (environmental and fiscal). To do this, we consider the specific connection between Paris, the French capital, and Marseille, the country's second largest city, and which is one of European origin-destination routes with the highest level of traffic. On this link, the plane is mainly in competition with the high-speed train and the private car (carpooling and buses accounting for marginal shares). We calibrate an intra- and intermodal competition model based on logit demand functions from 2019 traffic data and simulate the introduction of a Pigouvian tax (taking this tax equal to 190€ per ton of CO_2, i.e., the value of the externality estimated in recent studies).[1,2] We show that the impact on welfare is relatively small because the positive effect induced by reductions in externalities (some car and airplane users are giving up travel or switching to the less polluting train) is offset by the loss of utility for the users (renunciation of travel, or choice of a less preferred mode of transport) and the loss of profit for the airline operator. Specifically, the increased carbon tax significantly reduces consumer surplus, as it compels many users to forgo travel. This 'forced sobriety' cost highlights the substantial political opposition that can arise from introducing a carbon tax.

We also consider the impact of regulation on the pollution induced by the transport sector, taking into account the price regulation as prices on the French high-speed rail services are capped. Note that this price regulation is indirectly offset by the subsidy policy received by the infrastructure manager which is

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[1] In the sequel, all amounts of CO_2 emissions are in terms of CO_2 equivalent.
[2] We use a value of €190 per tCO_2 in 2019, consistent in order of magnitude with recent estimates—whether based on the social cost of carbon (EPA, 2023) or the shadow price implied by an emissions constraint (Gollier, 2025). Tutelary carbon values were set in France at around €165 per ton in 2019 (Quinet, 2019), and subsequently increased to approximately €225 in 2025 (France Stratégie, 2025). The value used here lies between these two benchmarks.

partly financed by the State.[3] Our model initially incorporates these constraints, enabling us to see the impact described above of carbon taxation and the advent of the electric car in the absence of any strong reaction on rail prices. In further simulation, we relax these constraints completely, allowing us to analyze the effect of price regulation on welfare, as well as the impact of a Pigouvian tax in the absence of rail regulation. Our analysis reveals that rail regulation induces a very positive effect on consumer surplus (with more than a million additional transports in the year), and a reduction in negative environmental externalities of the same order as that observed when a Pigouvian carbon tax is introduced (due to a significant modal shift from car and plane to train).

Finally, this study allows us to assess the impact of a carbon tax, and how it interacts with other policy measures. From a welfare point of view, as the transport market is imperfect, it is not always optimal to implement a Pigouvian tax, i.e. to set the level of the carbon tax at the value of the negative externality. We show that, in the reference scenario, the optimal level of a carbon tax is significantly lower than the externality value €190/tCO_2 because of the airline operator's market power (a phenomenon akin to double marginalization). However, if the State were to consider raising a carbon tax only on cars, the optimal level of this tax would then be higher than that of a Pigouvian tax (because the rail operator's market power limits the modal shift from car to rail). The objective here is not to advocate for setting the tax at some specific level but to highlight that the optimal approach involves a combination of three policies addressing multiple market imperfections: Too many carbon emissions, uneasy access to public transportation, and lack of or delays in innovation for zero-emission vehicles. Regarding the latter, we consider scenarios in which all or part of the passenger car fleet is electrified. Intuitively, electrification has a strong positive effect on both consumer surplus and environmental externalities. In this scenario however, a Pigouvian tax has a significant negative impact on welfare, three times as great as in the reference scenario, as it primarily affects air transport and leads to a significant reduction in travel among users of this mode.[4] We also note that if the proceeds of the carbon tax are used to reduce tax distortions ("double dividend" effect), the effect of a Pigouvian tax on welfare becomes positive in the reference scenario (but remains negative in the electric car scenario mentioned above).

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[3] We will not revisit the rationale behind public intervention in this sector, which often results in high levels of State subsidy (see Preston, 2016, for a recent review) and, more recently, which has been a motivation for introducing more competition (e.g., the European directives that fostered the emergence of low-cost airlines and in-market competition for high-speed rail). The reasons for subsidizing are valid for intra-urban traffic (see Vickrey 1980), but to some extent also for long-distance traffic.

[4] In this case, the political obstacle to the introduction of such a tax is lower, since it concerns a smaller number of potential users. According to Dechezleprêtre et al. (2022), a majority of French people is ready to limit flying to preserve climate, and 45 percent would be in favor of a carbon tax on air travel, while 20 percent remain undecided.

2. Literature Review

Our work involves modeling intermodal competition between different transport modes. The literature on this subject is abundant but focuses mainly on competition between air and rail (e.g., Wang *et al.*, 2025, who analyze the impact of modal competition on GHG emissions). Fewer articles also consider road transport, as in our work. (See González-Savignat, 2004, Adler *et al.*, 2010, and Álvarez-SanJaime *et al.*, 2016.) In order to correctly model the choice behavior between several modes of transport, we rely on a discrete choice model following McFadden (1974) and Andersson *et al*. (1996), which is adequate for differentiated multiproduct markets.

The impact of the transport sector on the environment is analyzed in the literature, covering many aspects that are not considered here. (See Jiang et al., 2021, for a full review of the literature on this subject.) In particular, numerous studies have looked at the complementarity between rail and air transport. They show a potentially negative effect on the environment -- better accessibility of airport hubs via high-speed rail ultimately increasing air traffic which is termed as a feeding effect in the literature. (See Givoni and Banister, 2006, and Socorro and Viecens, 2013.) Our study focuses on the Paris-Marseille route, where such complementarity is marginal due to the train journey time of over 3 hours (the airline usually offers instead a flight with a short stopover in Paris). In addition, in most studies, the train itself has a negative impact on the environment, via local air pollution (LAP) and greenhouse gas (GHG) emissions. Here we focus on the effect on the climate via GHG emissions and consider that high-speed rail in France has only a relatively marginal impact on these emissions (letting aside the life-cycle effects linked to the manufacture of rail equipment). More precisely, we use recent data from the French railway infrastructure manager (SNCF Reseau, 2023) indicating that carbon emissions from high-speed train in France over the recent period amount to approximately 2.6 gCO_2 per passenger-km travelled (compared with 5.6 gCO_2 per passenger-km in 2005 according to Seguret, 2014, due to the decarbonization of the electricity production in France). Some studies consider different cases, as they consider journeys over several countries. This is notably the case for studies on the Paris-London route. (See D'Alfonso *et al.*, 2016, and Givoni, 2007.) The electricity used at the time under consideration, i.e, in 1998, was nearly 76 percent nuclear (and 12.5 percent hydroelectric) for France, compared with nearly 48 percent coal (and 22 percent gas) for the UK.

When there is no feeding effect, the literature confirms that the development of high-speed trains leads to lower CO_2 emissions. Dalkic *et al.* (2017) show a positive but relatively modest effect of high-speed trains in Turkey, since the modal shift to rail comes from emission-efficient buses (the share of air transport being negligible). Strauss *et al*. (2021) focus on mode substitution from air to train in China and show that it leads to 18 percent reduction in air carbon emissions. D'Alfonso *et al.* (2015) develop a theoretical model and show that there is a tradeoff between the substitution effect (shift from air to rail) and the traffic generation effect, then provide an estimation for the change in CO_2 emissions for the Paris-London market based on numerical simulation. (See D'Alfonso *et al.*, 2016.)

Few studies consider strategic reactions on prices with modal shifts to both air and road, with a complete welfare analysis. Some works show that those reactions can lead to adverse effects. Notably, Wang et al. (2025) show that subsidizing high-speed train is beneficial to emission reduction but may distort competition and lead to welfare loss in some situation. Note that, in their case, aviation emission tax revenues are transferred to train operators, fostering a form of tacit collusion. Also, Gu et Van (2022) show that airlines might reduce prices when facing a strong competitive pressure from high-speed train, inducing more air passengers hence more CO2 emissions. Although we do not observe such a behavior in our simulations, the effect of a Pigouvian tax is negative in most of our scenarios. This is not surprising given that the Pigouvian tax applies to an imperfectly competitive downstream market. To the best of our knowledge, it has never been documented in the transport literature, except that Brueckner and Zhang (2010) mention this possibility.

3. Data

We consider an important market in France, namely Paris–Marseille, connected with a 750 kilometers high speed rail infrastructure. This route represents a significant share of long-distance passenger traffic in France (approximately 15 percent of rail leisure traffic for 3-to-4-hours HST – high-speed train - trips, according to data provided by the infrastructure manager SNCF Réseau). We focus our analysis on passengers that travel for leisure purposes. Three main passenger travel modes are offered on this link: Rail, road (private car) and air. The rail service, provided with the high-speed train technology, allows for a real competition in terms of travel time between air and rail transport on this specific distance. Alternatively, private car presents the advantage of a greater flexibility in departure times.[5] In addition, we consider three type of high-speed rail services: namely first class (the so-called "TGV Inoui 1"), second class ("TGV Inoui 2") and the "low cost" (the so-called "TGV Ouigo").

Data on traffic, prices and marginal costs are provided by SNCF Reseau for the year 2019 and are presented in Table 1. These data are used at the calibration stage later. The different variables of our model are defined and measured in the following way. The annual traffic data is the total number of one-way tickets for passengers originating either from Paris or from Marseille. For each of the five travel alternatives we consider, the price, measured in euros, is the average price paid by the passengers. The marginal costs for

[5] Carpooling and bus transport, with respective market shares lower than one percent on this specific link, are neglected as non-competing options in our analysis.

rail transport cover the operating costs and the tolls. The values for air transport marginal costs are provided to us by Air France, the airline operating on this market.

Table 1: Paris-Marseille Traffic Annual Data (2019)

Transport service	# Passengers	Market Share	Price €	Marginal cost €
Rail 1st Class	451067	8.3%	62.3	45
Rail 2nd Class	1407107	26.0%	53.4	38
Rail Low Cost	1260150	23.2%	30.5	24
Air	591438	10.9%	110.7	70
Private Vehicle	1649816	30.4%	88.6	88.6

Note: The market shares sum to 98.8 percent. The 1.2 percent left represents other modes that are neglected in the analysis.

To perform our assessment of a carbon tax, we need data on the amount of CO_2 emissions for the air and road transport modes, that can be found on the website of the French Agency for Ecological Transition (ADEME). Specifically, CO_2 emissions are computed in the following way.

i. For private vehicle transport, ADEME indicates that 169 kg of CO_2 are emitted per private vehicle on the road and that 88 percent of these emissions concern the transport activity (as opposed to the manufacturing and maintenance of cars). Since the road distance between Paris and Marseille is 776 kilometers, and since, according to the French National Statistical Institute (INSEE) in 2018-2019, the average number of passengers in a car is 2.25, the CO_2 emissions per road passenger on this market can be computed as follows: 169 times 0.88 divided by 2.25, which is equal to 66.1 $kgCO_2$ per passenger.

ii. For rail transport emissions, according to ADEME, 2.3 grams of CO_2 (0.0023 $kgCO_2$) are emitted per passenger and per kilometer on a Paris to Marseille trip. Given the rail distance for the Paris to Marseille link is 750 kilometers according to SNCF Réseau, we can compute the CO_2 emissions per rail passenger as follows: 0.0023 multiplied by 750, which is equal to 1.725 $kgCO_2$ per passenger.

iii. For air transport, ADEME indicates that a passenger flying between Paris and Marseille emits on average 152 $kgCO_2$.

To sum up, on the Paris to Marseille market, CO_2 emissions per passenger are estimated respectively at 0.001725 tons of CO_2 for rail transport, 0.152 tCO_2 for air transport and 0.0661 tCO2 for private vehicle transport. In 2019, a carbon tax is already in place, but at a lower level than that subsequently considered in our simulations. It was implemented for air and rail through the European Trading System market (EU ETS) at a price of 25 euros per tCO_2. For the individual car, it took the form of a tax on gasoline that remained blocked at 44.6 euros per tCO_2 following the Yellow Vests protests in 2018.

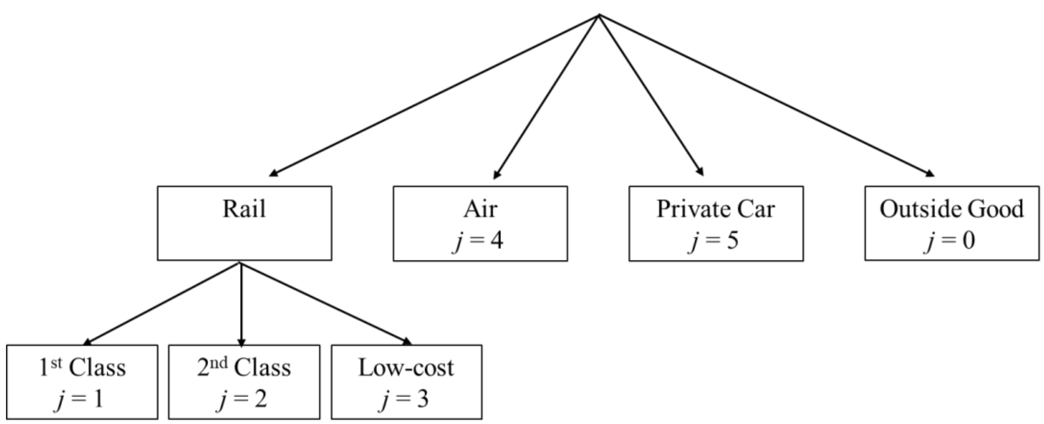
4. A Model of Intermodal Competition

We present a framework aimed at capturing intermodal competition between transport modes. We consider price competition among transport operators assuming that, in the short run, their transport services (in terms of quality or frequency among other characteristics) are considered as given. We first describe the demand side, and then characterize the determination of prices by operators involved in a Bertrand-Nash competition.

4.1. Demand side

Travel demand between Paris-Marseille is represented by nested logit model according to Figure 1. As presented in the preceding section on data, the passenger has the choice between five transport services: first-class rail, second-class rail, low-cost rail, air, and private car, which we denote by j = 1, 2, 3, 4, 5. The passenger can also choose the alternative of not traveling, that is called the outside good denoted by j = 0.

Figure 1:Nested logit model



A passenger i is assumed to chose an alternative j to maximize the indirecy utility:

$$U_{ij} = V_j + \varepsilon_{ij}\,, \tag{1}$$

where V_j is mean valuation of the transport service common to all passengers, which depends on its specific attributes. The random term, ε_{ij}, which follows a Gumbel distribution, captures unknown information and can account for the optimization errors that could happen in choosing an alternative. It corresponds to the deviation of passenger i from this common utility level, a function of passenger i's idiosyncratic preferences for product j.

The nested model allows for the correlation of this random error term among alternatives within a nest. Here, for the alternatives within the rail nest, i.e., when $j \in \{1,2,3\}$, we assume that the error term is decomposed in two error terms as:

$$\varepsilon_{ij} = \varepsilon_{i,rail} + (1-\sigma)\tilde{\varepsilon}_{ij}, \tag{2}$$

and that those terms also follow independent Gumbel (0, 1) distributions. The parameter σ gives a measure of the degree of correlation between alternatives belonging to the rail nest. It lies between 0 and 1. The higher σ, the higher the correlation between alternatives in the rail group. When $\sigma = 0$, one obtains a simple logit model.

The component V_j is defined as:

$$V_j = \psi_j - hp_j = \bar{\psi}_j + \xi_j - hp_j, \tag{3}$$

where ψ_j is a quality index for transport service *j* (comprising a deterministic part $\bar{\psi}_j$ and a random part ξ_j) and p_j, its price. The parameter *h* represents the marginal utility of income. Since we do not observe neither the quantity, nor the the price of the outside good, its utility is normalized such that: $V_0 = \psi_0 - hp_0 = 0$. This is a common assumption to avoid underidentification in logit models and it is coherent with the property of homogeneity of degree zero of logit demand functions.

Under these assumptions, following Ben-Akiva and Lerman (1985), one derives the nested logit probability of choosing a rail transport service, i.e., $j = \{1,2,3\}$ as the product $s_j = s_{rail} s_{j|rail}$, where the probability of choosing the train, s_{rail}, is obtained as:

$$s_{rail} = D_{rail}^{1-\sigma} / D, \tag{4}$$

and the probability of choosing rail transport service *j* conditional on choosing the train is given by:

$$s_{j|rail} = \exp\left(V_j / (1-\sigma)\right) / D_{rail}, \tag{5}$$

where $D = 1 + D_{rail}^{1-\sigma} + \sum_{j=4,5} \exp(V_j)$ and $D_{rail} = \sum_{j=1}^{j=3} \exp\left(V_j / (1-\sigma)\right)$. For the other alternatives, the choice probabilities take the usual logit form:

$$s_j = \exp(V_j) / D, \forall j \in \{0,4,5\}. \tag{6}$$

Using the Berry (1994)'s transformation, the demand functions for rail transport services can be written as:

$$\ln(s_j) - \ln(s_0) = \psi_j - hp_j + \sigma \ln(s_{j|rail}), \quad \forall j \in \{1,2,3\}, \tag{7}$$

And, for the other alternatives, as:

$$\ln(s_j) - \ln(s_0) = \psi_j - hp_j, \quad \forall j \in \{4,5\}. \tag{8}$$

Because of the normalzation of $V_0 = 0$, the demand for the outisde good is trivial.[6]

At the aggregate level, the probability s_j coincides with the market share of transport mode *j* taken over the total market size, *N*, defined as the number of potential passengers on the market (that is to say, $N = \sum_{i=1}^{5} q_i + q_0$). While we observe the number of passengers q_j choosing one of the five transport services, $j \in \{1,2,3,4,5\}$, we do not observe q_0, which is the number of individuals choosing not to travel, and so *N*. We then cannot compute the so-called external market shares defined as $s_j = q_j / N = q_j \Big/ \left(\sum_{i=1}^{5} q_i + q_0 \right)$ for any $j \in \{0,1,2,3,4,5\}$, the internal market shares being defined as $\bar{s}_j = q_j \Big/ \sum_{i=1}^{5} q_i$ for any $j \in \{1,2,3,4,5\}$. However, the external market shares can be obtained from the internal market shares as $s_j = \bar{s}_j (1 - s_0)$.

In the sequel, it is useful to note that the demand equations (7) can be written as:

$$\ln\left(\bar{s}_j (1 - s_0)\right) - \ln(s_0) = \psi_j - hp_j + \sigma \ln\left(s_{j|rail}\right), \quad \forall j \in \{1,2,3\} \tag{9}$$

and the equations (8) as:

$$\ln\left(\bar{s}_j (1 - s_0)\right) - \ln(s_0) = \psi_j - hp_j, \quad \forall j \in \{4,5\} \tag{10}$$

4.2. Supply side

For the link we are considering, there is one airline providing the air service and one rail operator providing the three rail services. We assume a static Nash equilibrium, where the rail operator and the airline set ticket prices to maximize their own objective functions, treating other alternatives as given and potentially subject to regulatory constraints for rail (as we explain below). Additionally, for private vehicle transport, we assume that car users operate at marginal cost, i.e., $p_5 = c_5$, where c_5 is the private car marginal cost that it is measured. (See Table 1.)

Thus, the air operator chooses its fare price p_4 to maximize its profit, i.e.,:

$$\underset{p_4}{\text{Max}}\, \pi_{air} = (p_4 - c_4) q_4, \tag{11}$$

where c_4 is the marginal cost of providing the air service.

Following Cherbonnier *et al*. (2017), the rail operator's prices are significantly lower than what would be optimal for a monopolistic firm on the rail mode maximizing its unconstrained short-term profit.

[6] See Appendix 1 for further details on the derivation of logit demand functions.

There are several possible explanations for these choices, which result in low margins. These may be due to the current price regulation, the rail operator's strategy anticipating a possible tightening of this regulation, the threat of entry of a competitor, or the effect of political pressure likely leading to the deployment of too expensive networks and offers of service. Notably, the operator is fully owned by the French State, has a large share of its income coming from public funds, and mainly communicates on average and entry-level prices for high-speed trains. We model this situation by assuming that the operator is under pressure on both its average prices and the price of its low-cost tickets. Specifically, we assume that the rail operator's program is to solve:

$$\underset{p_1,p_2,p_3}{\text{Max}}\ \pi_{rail} = \sum_{j=1}^{3}\left(p_j - c_j\right) q_j - \mu\left(\sum_{j=1}^{3} p_j s_{j|rail} - \overline{p}_{rail}\right) - \lambda\left(p_3 - \overline{p}_3\right), \tag{12}$$

where the parameters μ and λ are associated with the two constraints on the average price and the entry-level price respectively, $\overline{p}_{rail}$ is the implicit ceiling average price of train transport services that is the result of regulatory or political requests, and $\overline{p}_3$ is the implicit ceiling price on low-cost services most probably caused by external competition conditions. Both constraints can be binding or non-binding and $\overline{p}_{rail}$ and $\overline{p}_3$ are unobserved. The parameters μ and λ measure the losses in terms of profit diverted to address the regulatory contraints. Let us call them the shadow costs of regulation. The objective function (10) has been obtained after a large number of attempts with other specifications. It is the only one with which we can rationalize the data presented in Section 3, that is to say, with which we obtain convergence of the optimization program used to obtain the solution of the Bertrand-Nash equilibrium approximating the intermodal competition, given the observed market shares, prices and marginal costs.

With only one year of data available on the single link under consideration, the next task is to calibrate the main parameters of our model. Naturally, the aim of a calibration exercise is not to attain statistical robustness. Instead, its purpose is to establish reasonable and meaningful values for the parameters of interest, thereby facilitating informatively sound simulations and counterfactuals.

5. Calibration

The parameters to calibrate are: The five quality parameters, ψ_j, the marginal utility of income, *h*, the degree of correlation among rail alternatives, σ, the shadow costs of regulation, μ and λ, and the internal share of non travelling individuals, s_0.

These ten parameters enter in a non-linear system of nine equations, formed with the five demand equations (7) and (8), the first-order condition associated with the profit maximization of the air operator (9) and the three ones associated with the profit maximization of the rail operator (10).

In this system, we replace the number of passengers, the prices and the marginal costs for the different modes by their observed values presented in Table 1. Then, we are in the position to solve the system for the unknow parameters.

However, to do so, one needs to fix one of the parameters since the number of parameters is larger than the number of equations. In a first approach, because quality parameters have no dimension and no physical unit, the most intuitive choice is to fix one of the parameters of quality to zero. Since the logit demand functions are microeconomically founded, the values of other quality parameters will adjust automatically to this choice, and the order of values for the quality parameters will be preserved. We propose to fix the quality parameter of private car to zero, i.e., $\psi_5 = 0$. We then evaluate whether this assumption is realistic for the values of other parameters.

The algorithm to solve the system of nine equations proceeds in two steps. First, we obtain the marginal utility of income *h*, the degree of correlation σ, the shadow costs of regulation μ and λ, and the external share of non travelling individuals, s_0, by solving the system formed with the demand function for private vehicle (Equation 10), and the four first order conditions associated with the profit maximization of rail and air operators, noticing that these five equations are not directly functions of the four unknown quality parameters ψ_j. Appendix 2 provides the expressions of the four first order conditions which are functions of *h*, σ, μ/N, λ/N, and s_0. Second, it remains to solve the three demand equations for rail transport (9) and the demand for air transport (10) for the four quality parameters ψ_j. This calibration procedure yields the values for the nine parameters gathered in Table 2, given the assumption $\psi_5 = 0$.

The question is now to assess the revelance and the realism of the parameters values. First, we discuss whether the value obtained for the share of non-travelling individuals, s_0, is credible. This value corresponds to a number of non-travelling individuals of around 15.481 million.[7] If this value is correct, then the total market size for the Paris-Marseille leisure market in our study, i.e., $N = \sum_{j=1}^{5} q_j + q_0$, is equal to 20.841 million of potential passengers (using the numbers of passengers travelling provided in Table 1).

[7] Since $s_0 = q_0 \Big/ \left(\sum_{j=1}^{5} q_j + q_0 \right)$, then $q_0 = \left(s_0 / (1 - s_0) \right) \sum_{j=1}^{5} q_j$.

Table 2: Results for the parameter calibration (first approach)

Name	Symbol	Value
Quality Rail 1st Class	ψ_1	-0.177
Quality Rail 2nd Class	ψ_2	-0.314
Quality Rail Low Cost	ψ_3	-0.900
Quality Air	ψ_4	-0.466
Quality Private Vehicle	ψ_5	0.000
Marginal utility of income	h	0.025
Degree of correlation	σ	0.923
Shadow cost of regulation	μ	665750
Shadow cost of regulation	λ	1641270
Number of non-travelling individuals	s_0	0.743

Note: In this first approach, the quality of the private vehicle is fixed.

The Paris–Marseille link that we are considering in this study concerns three areas: The Region Ile-de-France, where Paris is located, and the metropolitan urban area of Marseille as origin and destination of this link and the metropolitan area of Lyon which is the main stop in between. Considering the geometric mean (which is an usual measurement method for calculating the size of transport markets) of the populations of Paris'metropolitan area (7.12 million inhabitants), Lyon's metropolitan area (1.4 million), and Marseille's metropolitan area (1.83 million), which comes to 2.63 million inhabitants, and then multiply this by 13.4 (the average number of long-distance trips per year per person provided by the French Regulation Authority of Transports in 2022), yields 35.274 million potential passengers. This would represent the maximum market size including trips for all purposes, assuming identical access to all transport modes for all inhabitants. This figure could be overestimated because, for example, not all inhabitants of these metropolitan areas have the same level of access to the TGV or to airports. In the same time, it is also potentially underestimated as it does not account for passengers from other countries for instance.

Based on these estimates, the Paris-Marseille leisure transport market (20.841 million) represents 59.08 percent of the maximum market size of 35.274 million potential passengers. Is this proportion realistic? According to another study of the French Regulation Authority of Transports in 2019, 65 percent of passengers in high speed trains are travelling for leisure purposes. From the 2018-2019 personal mobility survey conducted by SDES in 2019 before the Covid-19 pandemic, 72 percent of long-distance trips (defined as journeys more than 80 km from home) are made for visiting or leisure purposes. This would mean that our calibration would lead to an underestimation of the size of the leisure market, and therefore probably the number of people who do not travel for leisure purposes. The consequence is that we would overestimate price effects and therefore underestimate the effects on consumer surplus. However, since these estimates of market sizes are not drastically different, the overestimations or underestimations are certainly small and cannot change the nature and direction of our results.

Based on these remarks, our estimate of the number of non travelling individuals (and its share of 74 percent of our market size of 20.841 million potential passengers), is realistic. Does it yield realistic values for the other parameters of interest? The following comments tend to support a positive reply.

First, the degree of correlation among rail alternatives, σ, is equal to 0.923, which shows that the correlation among the rail alternatives is high, which is what we can expect given that the three rail services obviously shares many features.

Second, we observe that the quality of all modes are lower than the one of private vehicle, reflecting the much higher availability of a car compared to a train or a plane. Note that the quality of the three rail services, $\psi_j \; j \in \{1,2,3\}$, are ranked as expected with the highest quality for the first class of high speed train and the lowest one for the low-cost high speed train. It could be surprising that the quality of air transport is lower than the ones of the first two rail services. This may reflect the advantages in terms of the comfort of high-speed train seats, the convenience of arriving in a city center where train stations are located, and the difficulties in accessing airports.

Finally, to test for the coherency of calibrated values of the ten parameters, we solve, as a second appoach, the preceding algorithm this time assuming that the share of non travelling individuals is equal to 75 percent, which is in adequacy with our evaluation of market sizes. In this case, the calibration provides the parameter values gathered in Table 3. We observe that, as expected, they are close to those of Table 2, supporting the view that the solution obtained is stable and well identified.

Table 3: Results for the parameter calibration (second approach)

Name	Symbol	Value
Quality Rail 1st Class	ψ_1	-0.216
Quality Rail 2nd Class	ψ_2	-0.353
Quality Rail Low Cost	ψ_3	-0.939
Quality Air	ψ_4	-0.506
Quality Private Vehicle	ψ_5	-0.039
Marginal utility of income	h	0.025
Degree of correlation	σ	0.923
Shadow cost of regulation	μ	665750
Shadow cost of regulation	λ	1637955
Share of non-travelling individuals	s_0	0.750

Note: In this second approach, we fix the share on non-travelling individuals.

For now on, we consider the results of Table 3. With these values, the number of non-travelling individuals is equal to 16078732 and the total market size for the Paris-Marseille leisure market, i.e., $N = \sum_{j=1}^{5} q_j + q_0$, is equal to 21.438 million of potential passengers.

Note that the shadow costs of regulation μ and λ are expressed in terms of number of potential passengers and represent 3.11 percent and 7.64 percent of the market size, respectively. Both are different from zero, which means that the associated economic constraints in Equation (12) are binding. In other words $\sum_{j=1}^{3} p_j s_{j|rail} - \overline{p}_{rail} = 0$ and $p_3 - \overline{p}_3 = 0$.

Using the parameter values, we can compute the own- and cross-price elasticity of demand functions. They are provided in Table 4. As mentioned above, although we cannot rely on econometric tests, we can nevertheless guarantee a certain robustness of our methodology by checking that the calibrated model delivers correct results when comparing its predictions to those obtained in the literature. The literature provides a range of estimates for the price elasticities of demand, which naturally vary according to the possibilities of inter-modal transfers, themselves a function of the distance to be covered. The values obtained of the own-price elasticities provided in the following table are significantly higher than those measured on average for long-distance networks, which is natural when considering a specific, very long link where competition with other modes of transport is stronger. (See Börjesson, 2014, for the Swedish network, and Wardman, 2022, for the British network.) However, the values obtained are consistent with those obtained on specific high-speed train routes, such as Cologne-Berlin obtained by Ivaldi and Vibes (2008) or Valencia-Madrid provided by Ortega Hortelano *et al*. (2016).

Table 4: Own- and cross-price elasticities

	Rail 1st Class	Rail 2nd Class	Rail Low Cost	Air	Private Vehicle
Rail 1st Class	-17.52	7.34	3.76	0.08	0.17
Rail 2nd Class	2.75	-10.09	3.76	0.08	0.17
Rail Low Cost	2.75	7.34	-6.21	0.08	0.17
Air	0.03	0.09	0.05	-2.72	0.17
Private Vehicle	0.03	0.09	0.05	0.08	-2.06

Note: Each cell (*i,j*) represents the change in quantities of transport service *i* as the result of a one-percent price increase of transport service *j*. See Appendix 1 for the computations of these elasticities.

Since we are considering the leisure market, it is not surprising that the price elasticity for the rail 1[st] Class takes the highest value. Indeed, any small price change in this high-quality service causes a switch to other cheaper alternatives which finally provide relatively close services in terms of transport time and frequencies. This is confirmed by the high degree of substitutability between rail alternatives as measured by the cross-price elasticities. The cross elasticities between the other modes are relatively low, which can be explained by their very different characteristics like the location of airports versus that of train stations, long journey times by car, or higher flexibility of cars.

6. Simulations

Our calibrated model allows us to evaluate the welfare effects of various alternative scenarios.

6.1. Two scenarios on the impact of a carbon tax

To evaluate the welfare effects of a carbon tax in this context of intermodal competition in the long-distance passenger market, we first implement two simulations with an increase in the carbon tax to 130€/tCO_2 (scenario 1) and to 190€/tCO_2 respectively (scenario 2) from its reference situation of 2019 in which the carbon tax is equal to 25€/tCO_2 for rail and air transport services, and to 44.6€/tCO_2 for road transport. We assume that the value of the negative environmental externality induced by greenhouse gases (GHG) is equal to 190€/tCO_2, which is close to the academic consensus. (See EPA, 2023.) Thus, the second scenario amounts to implementing a Pigouvian carbon tax, the value of which would fully internalize the negative externality.

As Table 5 shows, the increase in the carbon tax has a significant impact on airline market share, which falls by nearly 40 percent in scenario 2, although the airline operator limits the decrease of its margin rate by passing a part of the tax increase to customers. This can be explained by the relatively low cross-price elasticity of airline demand. (See Table 4.) Note the lack of strategic response from the rail operator, which keeps its prices unchanged, partly due to the regulatory constraints discussed in Section 4. Rail market share increases slightly. Consequently, 84 percent of passengers—either those lost by the air operator or those abandoning their private vehicles due to the carbon tax increase—choose not to travel, with only the remaining percentage switching to rail.

We are also interested in the impact of the increase in carbon tax on total welfare and its different components. The overall impact is derived by combining the effects on consumer surplus, transport operators' profits, and taxes collected by the State, along with the decrease in environmental externalities, according to the following equation:

$$\Delta \text{Welfare} = \Delta \text{Consumer Surplus} + \Delta \text{Profit Transport Operators} + \Delta CO_2 \text{ Taxes} - \Delta CO_2 * E \qquad (13)$$

where E is the value of negative environmental externalities induced by greenhouse gases. We assume in the sequel that E is equal to 190€/tCO_2.

Table 5: Impact of an increase in carbon tax

		Reference	Scenario 1 Carbon tax 130€/tCO_2	Scenario 2 Carbon tax 190€/tCO_2
Internal market share (%)	Rail 1st Class	8.4	9.2	9.6
	Rail 2nd Class	26.3	28.4	29.7
	Rail Low Cost	23.5	25.5	26.7
	Air	11.0	8.1	6.7
	Private Vehicle	30.8	28.8	27.2
# Passengers (Million)	Rail 1st Class	0.5	0.5	0.5
	Rail 2nd Class	1.4	1.4	1.4
	Rail Low Cost	1.3	1.3	1.3
	Air	0.6	0.4	0.3
	Private Vehicle	1.7	1.5	1.3
	Non-travelling	16.1	16.4	16.6
Price	Rail 1st Class	62.3	62.3	62.3
	Rail 2nd Class	53.4	53.4	53.4
	Rail Low Cost	30.6	30.6	30.6
	Air	110.7	126.3	135.3
	Private Vehicle	88.6	94.2	98.2
Marginal cost	Rail 1st Class	45.0	45.2	45.3
	Rail 2nd Class	38.0	38.2	38.3
	Rail Low Cost	24.0	24.2	24.3
	Air	70.0	86.0	95.1
	Private Vehicle	88.6	94.2	98.2
Margin rate (%)	Rail 1st Class	27.8	27.5	27.3
	Rail 2nd Class	28.9	28.5	28.4
	Rail Low Cost	21.4	20.9	20.5
	Air	36.8	31.8	29.5
	Private Vehicle	0.0	0.0	0.0

This measure of welfare does not account for the utilization of carbon tax revenues to mitigate tax distortions. More precisely, the revenues from the carbon tax could facilitate a reduction in other obligatory levies, for instance those impacting labor. These levies exert a distorting influence, as every euro collected carries an associated cost, termed the "opportunity cost of public funds," which Quinet (2013) estimates at €0.20 in France. Naturally, this "double dividend" may not materialize if tax revenues are channeled towards alternative objectives (e.g., disbursed as a lump-sum transfer). In any case, to account for the cost of public funds, the welfare must be computed according to this equation:

$$\Delta \text{Welfare} = \Delta \text{CS} + \Delta \text{Profit} + \Delta \text{CO}_2 \text{ Taxes} \left(1 + 0.2\right) - \Delta \text{CO}_2 * \text{E} . \quad (14)$$

As Table 6 shows, the total impact on well-being is negative in both scenarios but very small, between one and two percent of total welfare. In other words, the increase of carbon tax to 130 or 190€/tCO_2 is nearly neutral and quasi-neutral if one accounts for the opportunity cost of public funds.

This aggregate result, however, masks larger effects on the different components of the welfare. On the one side, there is, as expected, a strong positive effect on externalities (GHG emissions) and the amount of the carbon tax that is collected. On the other side, the airline faces a significant loss of profit and there is a highly negative effect on consumer surplus, reflecting the fact that it leads many users to forgo travel. The cost of this "forced sobriety" clearly demonstrates the potential for significant political opposition to implementing a carbon tax.

Table 6: Welfare analysis of an increase in carbon tax

	Scenario 1 Carbon tax 130€/tCO_2		Scenario 2 Carbon tax 190€/tCO_2	
Change	Million €	Percent	Million €	Percent
Consumer surplus	-16.5	-6.8	-25.3	-10.4
Rail operator's profit	+0.2	+0.4	+0.2	+0.6
Airline's profit	-7.7	-31.9	-10.9	-45.3
Tax revenue	+14.0	+193.7	+20.0	+276.2
Environmental externalities	-7.7	-19.9	-11.6	-29.8
Welfare	-2.3	-0.8	-4.4	-1.6
Welfare under cost of public funds	+0.6	+0.2	-0.4	-0.1

Note: Changes are computed with respect to the reference situation.

6.2. Deregulation of rail prices

We now analyze the impact of rail price regulation in France through the very specific example of the Paris-Marseille route. To do so, we first look at the impact of lifting regulatory constraints on rail prices (scenario 3), second, at the effect, in this deregulated situation, of a Pigouvian carbon tax (scenario 4), that is, at the impact of deregulation under a carbon tax at €190/tCO_2. Table 7 shows the impact on traffic and prices, while Table 8 shows the impact on welfare.

Table 7 shows that deregulating the rail prices (keeping the level of taxes constant) would have a significant impact on the air and road traffic. The market share of air transport would rise from 11 to 16 percent and that of the private car from 31 to 45 percent. Even the air transport operator's profit increases.

Table 8 shows that deregulating rail prices would severely harm welfare, negatively impacting both consumer surplus and externalities. Maintaining pressure on the rail prices effectively subsidizes the cleanest mode of transportation. Note that the price regulation also has a redistributive effect: Rail passengers are opting out of low-cost services, those that clearly benefit most from price regulation. The model also predicts that the volume of rail traffic is almost halved and that no more than 7 percent of these fewer rail passengers are transferred to the air and road transport modes. Most of the passengers giving up rail decide not to travel any more.[8]

[8] Note that the strong effect of rail price deregulation has similar effect as a significant change in the rail supply, moving from a "classical" train to a HST. Givoni and Dobruszkes (2013) provide a review of the literature on this

Table 7: Impact of rail price deregulation

		Reference	Scenario 3	Scenario 4
			Deregulation	Deregulation and Carbon tax 190€/tCO_2
Market share (%)	Rail 1st Class	8.4	14.7	17.5
	Rail 2nd Class	26.3	24.6	29.4
	Rail Low Cost	23.5	1.2	1.5
	Rail	58.2	39.7	48.3
	Air	11.0	15.9	10.2
	Private Vehicle	30.8	44.4	41.5
Price	Rail 1st Class	62.3	87.9	88.3
	Rail 2nd Class	53.4	80.9	81.3
	Rail Low Cost	30.6	66.9	67.3
	Air	110.7	110.8	135.3
	Private Vehicle	88.6	88.6	98.2
# Passengers (Million)	Rail	3.1	1.7	1.7
	Air	0.6	0.6	0.3
	Private Vehicle	1.7	1.8	1.5
	Non-travelling	16.1	17.0	18.0

Table 8: Welfare analysis of deregulation

	Scenario 3		Scenario 4	
	Deregulation		Deregulation and Carbon tax 190€/tCO_2	
Change	Million €	Percent	Million €	Percent
Consumer surplus	-67.8	-27.8	-93.6	-38.4
Rail operator's profit	+30.6	+81.0	+34.6	+91.8
Airline's profit	+2.0	+8.3	-9.8	-40.7
Tax revenue	+0.5	+7.2	+21.7	+299.5
Environmental externalities	+2.6	+6.7	-9.9	-25.5
Welfare	-37.3	-13.5	-37.2	-13.5
Welfare under cost of public funds	-37.2	-13.5	-32.9	-11.9

Note: Changes are computed with respect to the reference situation.

The impact of a €190/tCO_2 tax within a deregulated economy, as presented in the final two columns of Table 8, reveals a reallocation and resizing of various welfare components. Notably, this occurs without a change in the overall welfare loss, and the reduction of externalities remains moderate.

6.3. Widespread adoption of electric vehicles

We now consider the impact of the electrification of the whole vehicle fleet without and with a

question and show that the development of high-speed rail links induces relatively moderate additional demand over short distances (around 20 percent for distances of around 200-300km. such as Rome-Naples). but much higher demand over longer distances (about 50 percent for 470km Paris-Lyon route. according to Bonnafous 1987).

€190/tCO_2 carbon tax (corresponding to scenarios 5 and 6). Here we assume that the marginal cost of the electric vehicle is evaluated at €85 according to the website ViaMichelin, slightly inferior to the marginal cost of the thermic private vehicle of €88.6 from the reference situation (in Table 1). Tthere is not much impact in terms of market shares and prices, as reported in Table 9. The number of passengers for rail and air transport modes decreases slightly to the profit of private electric vehicles.

Table 10 shows the impact on welfare. As expected, the shift to electric vehicles (EV) results in a very significant reduction in GHG emissions, comparable in magnitude to imposing a Pigouvian tax in the reference scenario. Given the relative stability of transport operators' profit, as shown in the third and fifth columns of Table 10, the reduction in environmental externalities directly translates into a significant welfare increase. Note however that, without a carbon tax, the widespread adoption of the electric vehicles boosts consumer surplus, while it simultaneously diminishes the government tax revenue.

Table 9: Impact of widespread adoption of electric vehicles

		Reference	Scenario 5	Scenario 6
			EV	EV and Carbon tax 190€/tCO_2
Market share (%)	Rail 1st Class	8.4	8.2	8.7
	Rail 2nd Class	26.3	25.5	26.8
	Rail Low Cost	23.5	22.8	24.1
	Air	11.0	10.7	6.1
	Private Vehicle	30.8	32.7	34.4
Price	Rail 1st Class	62.3	62.3	62.3
	Rail 2nd Class	53.4	53.4	53.4
	Rail Low Cost	30.6	30.5	30.5
	Air	110.7	110.7	135.3
	Private Vehicle	88.6	85.0	85.0
# Passengers (Million)	Rail	3.1	3.1	3.1
	Air	0.6	0.6	0.3
	Private Vehicle	1.7	1.8	1.8
	Non-travelling	16.1	16.0	16.1

Table 10: Welfare analysis of widespread adoption of electric vehicles

	Scenario 5		Scenario 6	
	EV		EV and Carbon tax 190€/tCO_2	
Change	Million €	Percent	Million €	Percent
Consumer surplus	+6.2	+2.5	-4.7	-1.9
Rail operator’s profit	-0.3	-0.7	-0.7	-1.8
Airline’s profit	-0.2	-0.7	-11.2	-46.6
Tax revenue	-4.9	-67.4	+3.0	+41.7
Environmental externalities	-20.9	-53.7	-28.6	-73.6
Welfare	+21.7	+7.5	+15.0	+5.7
Welfare under cost of public fund	+20.7	+7.5	+15.6	+5.7

Note: Changes are computed with respect to the reference situation.

7. Conclusion

To our knowledge, and according to the literature review provided in Section 2 above, the present study is the first one that evaluates the welfare impact of a carbon tax in the context of an inter- and intra-modal competition model.

The main results are the following. First, a 190€/tCO2 carbon tax is nearly welfare-neutral but highly detrimental to consumer surplus. Second, rail price regulation has the side effect of reducing GHG emissions by subsidizing the cleanest transport mode. Third, widespread adoption of the electric vehicle is welfare enhancing without being too harmful to the consumer surplus.

These results are, however, obtained in the context of a single link, namely the market for transport services between Paris and Marseille. While it is one of European origin-destination route with the highest level of traffic, it would be useful to test these results on other routes because many socioeconomic and physical characteristics (like the size of population at origin and destination, the topology of the transport infrastructures, the quality of services) could affect the density of the traffic and the modal shares from one route to the other.

Moreover, given that only one year of data is available to us, we are in the position to calibrate the parameters of our model and not to statistically estimate them. Although we provide evidence that the calibrated parameters we obtain are fairly realistic, it remains that we have no way to assess for their significance and robustness. Nonetheless, given that most data on transport services and in particular on HST traffic are confidential and sensitive because of the competition among transport operators, our method provides a pragmatic, efficient and informative way to assess the relevance of transport policies, without the need to count on large sources of information.

Further analysis within this framework could explore the following directions. Here, we have simulated the impact of different policies taken alone. Could we find a combination of policies that would yield to increases in consumer surplus and welfare? What would be an optimal carbon tax in this perspective? Addressing these questions would require developing specific algorithms, which is at this point well beyond the scope of the present study.

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Appendix1: Derivation of logit demand equations

For the specific model described by Figure 1, the vector of random terms, $\varepsilon_{ij}, j \in \{0,1,2,3,4,5\}$, entering in Equation (1) introduced in the core text, has the cumulative distribution:

$$\exp\left(-\sum_{k=0,4,5}\exp(-\varepsilon_{ik})-\left(\sum_{k=1,2,3}\exp\left(-\frac{\varepsilon_{ik}}{1-\sigma}\right)\right)^{1-\sigma}\right).$$

Based on this specification and following Ben-Akiva and Lerman (1985), the probability of choosing alternative $j \in \{1,2,3\}$ is obtained as:

$$s_j = \frac{\exp(V_j)(s_{j|rail})^{\sigma}}{\left(\sum_{k=0,4,5}\exp(V_k)\right)+\left(\sum_{k=1,2,3}\exp\left(\frac{V_k}{1-\sigma}\right)^{1-\sigma}\right)}$$

where:

$$s_{j|rail} = \frac{\exp\left(\frac{V_k}{1-\sigma}\right)}{\sum_{k=1,2,3}\exp\left(\frac{V_k}{1-\sigma}\right)}.$$

Then it is straitforward to derive Equations (4) and (5). Now the probability of choosing alternative $j \in \{0,4,5\}$ is obtained as:

$$s_j = \frac{\exp(V_j)}{\left(\sum_{k=0,4,5}\exp(V_k)\right)+\left(\sum_{k=1,2,3}\exp\left(\frac{V_k}{1-\sigma}\right)^{1-\sigma}\right)}.$$

Applying the Berry (1994)'s transformation, one easily derives the demand function in Equations (7) and (8).

We can then derive the expressions for the elasticities. First, observe that

$$\frac{\partial s_0}{\partial p_j} = hs_0 s_j \ \forall j \in \{1,2,3,4,5\},$$

and that

$$\frac{\partial s_{j|rail}}{\partial p_j} = -\frac{h}{1-\sigma}s_{j|rail}\left(1-s_{j|rail}\right) \forall j \in \{1,2,3\}$$

and

$$\frac{\partial s_{j|rail}}{\partial p_k} = -\frac{h}{1-\sigma}s_{j|rail}s_{k|rail}(1-) \ \forall j,k \in \{1,2,3\} \ j \neq k,$$

where $s_{j|rail} = q_j \Big/ \sum_{i=1}^{3} q_i \ \forall j \in \{1,2,3\}$.

Second, differentiating the probability of choosing a transport mode provided above with respect to price yields:

$$\frac{\partial s_j}{\partial p_j} = -hs_j\left[\left(1-s_j\right)+\frac{\sigma}{1-\sigma}\left(1-s_{j|train}\right)\right] \quad \forall j \in \{1,2,3\}$$

$$\frac{\partial s_j}{\partial p_k} = hs_k\left[s_j+\frac{\sigma}{1-\sigma}s_{j|train}\right] \quad \forall j,k \in \{1,2,3\}\ j \neq k$$

$$\frac{\partial s_j}{\partial p_j} = -hs_j\left(1-s_j\right) \quad \forall j \in \{0,4,5\}$$

$$\frac{\partial s_j}{\partial p_k} = hs_k s_j \quad \forall j,k \in \{0,4,5\}\ j \neq k$$

Appendix 2: First-order conditions for transport operators' profit maximization programs

The three first order conditions associated with the railway operator's profit maximization program in Equation (12) with respect to prices p_i with $i \in \{1,2,3\}$ are:

$$s_j + \sum_{k=1}^{3}\left(p_k - c_k\right)\frac{\partial s_k}{\partial p_j} - \frac{\mu}{N}\left(s_{j|rail} + \sum_{k=1}^{3} p_k \frac{\partial s_{k|rail}}{\partial p_j}\right) = 0 \quad \forall j \in \{1,2\} ,$$

$$s_j + \sum_{k=1}^{3}\left(p_k - c_k\right)\frac{\partial s_k}{\partial p_j} - \frac{\mu}{N}\left(s_{j|rail} + \sum_{k=1}^{3} p_k \frac{\partial s_{k|rail}}{\partial p_j}\right) - \frac{\lambda}{N} = 0 \quad \text{when} \quad j = 3 ,$$

where $s_j = \bar{s}_j\left(1-s_0\right)$, $N = \left(\sum_{i=1}^{5} q_i\right) \Big/ \left(1-s_0\right)$, and $\bar{s}_j = q_j \Big/ \sum_{i=1}^{5} q_i$ where q_j is the observed number of passengers for transport mode $j \in \{1,2,3,4,5\}$.

After simplification, the first order condition associated with the air operator's profit maximization program in Equation (11) is:

$$p_4 - c_4 = \frac{h}{1-\bar{s}_4\left(1-s_0\right)} .$$