Tradable mobility credits for long-distance travel in Europe

Tanner, Sandro; Provoost, Jesper; Cats, Oded

DOI
10.1016/j.tra.2024.104156

Publication date
2024

Document Version
Final published version

Published in
Transportation Research Part A: Policy and Practice

Citation (APA)
Tanner, S., Provoost, J., & Cats, O. (2024). Tradable mobility credits for long-distance travel in Europe. *Transportation Research Part A: Policy and Practice*, *186*, Article 104156. https://doi.org/10.1016/j.tra.2024.104156

Transportation Research Part A 186 (2024) 104156

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Tradable mobility credits for long-distance travel in Europe

Sandro Tanner [a,b], Jesper Provoost [a], Oded Cats [a,*]

[a] *Department of Transport & Planning, Delft University of Technology, Stevinweg, 2628 CN Delft, Netherlands*
[b] *Institute for Transport Planning and Systems, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland*

ARTICLE INFO

Keywords:
Long-distance travel
Tradable mobility credits
Pricing
Modal split
Demand management

ABSTRACT

There is an urgent need to devise policy instruments that will reduce GHG emissions to a sufficient extent in order to achieve the climate targets. Approximately 16% of all greenhouse gas emissions are generated by long-distance travel. Our objective is to estimate the impact of a Tradeable Mobility Credit (TMC) scheme – where the total emissions are fixed by design whereas the price is the outcome of travelers' choices – will have on modal split and trip cancellation for long-distance leisure travel in Europe. To this end, we develop a market equilibrium model which accounts for travel and trading decisions. For our case study consisting of a travel demand of more than 300 million trips performed annually between 3,000 city-pair connections, the credit price that emerges in the market equilibrium state is 272€ per ton of CO2 under an emission reduction target of 30%. Due to the TMC, overall long-distance leisure travel demand is reduced by 20% and the share of air among the remaining trips decreases from 50 to 42% whereas the market share of rail increases from 23 to 26%. Modal shifts and trip cancellation rates vary greatly amongst OD-pair connections, depending on the local value-of-time and the extent of modal competition for the respective connection. Our findings contribute to the on-going debate surrounding instruments for stimulating sustainable (im)mobility, in particular in the context of the long-distance travel market.

1. Introduction

1.1. Long-Distance travel

To achieve the goals set by the Paris Agreement, GHG (greenhouse gas) emissions must be drastically reduced, and the transport sector must contribute to it. The transport sector produces 29 % of all GHG emissions in the European Union in 2019 (European Environment Agency, 2021). More than half of passenger-transport related climate effects are generated by long-distance trips of 100 km or more. Petersen et al. (2009) found that while the number of trips of more than 100 km makes up about 2.5 % of all trips in Europe, these trips account for about 55 % of all passenger-kilometers travelled. Nevertheless, long-distance travel is understudied in transport research and is known to be underrepresented in travel behavior data (van Goeverden, 2009). This discrepancy between the relevance of long-distance travel for emission reduction policy goals and the lack of knowledge to support related decision making has led to calls for increasing research efforts in this field, see for example Rich and Lindhard (2012) and Reichert et al. (2016). The former concluded that "with increasing focus on climate effects, long-distance travel demand modelling is likely to be at the top of the applied research agenda for years to come". In Europe, the vast majority of long-distance trips are for leisure (see Aparicio 2016 and Åkerman

* Corresponding author.
E-mail address: o.cats@tudelft.nl (O. Cats).

https://doi.org/10.1016/j.tra.2024.104156
Received 23 May 2023; Received in revised form 23 June 2024; Accepted 25 June 2024
Available online 30 June 2024

et al. 2021 for their analysis of data from France and Sweden, respectively).

The main travel modes for long-distance travel in Europe are airplane, train and car. The emissions per passenger-kilometer of a transport mode depend on many factors like vehicle occupancy, type of fuel or electricity mix, and type of propulsion. Usually, from an environmental perspective, travelling by rail is associated with producing fewer emissions than travelling by car or plane. According to the values indicated by Milieu Centraal et al. (2024), the CO_2 emissions associated with travelling by air are about 6 to 8 times higher than those associated with travelling by rail. Depending on the travel distance and the composition and efficiency of both vehicle fleets, car travel may be more or less polluting than air travel. One key policy goal for drastically reducing the contribution of aviation to climate change is “reduced growth in air travel through a shift towards train trips” (Bleijenberg, 2020). Åkerman et al. (2021) emphasizes that modal shift is seen as the main potential for reducing GHG emissions from transport. This can be achieved by the implementation of demand-management transport policy strategies. Demand management strategies aim to set the right incentives so as to stimulate a more sustainable travel behavior. Taxation is the most commonly applied instrument in both road transport and aviation. Taxes are applied when purchasing flight tickets and are not directly related to the associated emissions, albeit a differentiation between short- and long-haul flights is sometimes made, and tax levels vary significantly amongst European countries. Consequently, their environmental effectiveness is limited. On the one hand, the actual emissions are not considered. On the other hand, the national implementations induce tax competition, which can be perceived as unfair as well potentially leading to capacity shifting to other markets thereby resulting in a general tendency towards under-taxation (Denstadli & Veisten, 2020).

1.2. Tradable mobility credits

There is an urgent need to devise policy instruments that will reduce GHG emissions to a sufficient extent in order to achieve the climate targets. In the urban context, growing attention has been given in the past decades to market-based pricing instruments such as congestion charging and tradeable mobility credits (TMC). These instruments can be designed to reduce the externalities associated with motorized transport, and the private car in particular. TMC is seen as a promising instrument to drastically reduce emissions. Under a TMC, the number of credits needed to undertake a trip can depend for instance on the CO_2 emissions of the trip. Provoost et al. (2023) provide a framework for designing a TMC scheme and discusses the alternative design choices in relation to ownership, transfer and consumptions of such credits as well as related governance aspects. In such schemes, credits are allocated to citizens by a governmental institution. Citizens with a credit expenditure that exceeds the allocated credits can buy credits from citizens who do not use all their allocated credits. This trade happens in a centralized market. The price of the credit is therefore dynamic, and is the outcome of the equilibrium value that emerges from the current relation between demand and supply. Total emissions are capped by the amount of credit supply introduced into the market. A TMC scheme is yet to be implemented in practice. However, it can be compared to existing concepts which have been proven to be successful, like the EU emission trading system (ETS), fishing quotas, and airport slot allocations (Dogterom, Ettema, & Dijst, 2017). In contrast to these concepts, TMC are distributed and consumed by individuals and not on a firm or industry level.

While in the case of taxation schemes the price is fixed and total emissions are not directly limited but rather the outcome of travelers’ choices, for TMC this is the other way around, i.e. the total emissions are fixed by design whereas the price is the outcome of travelers’ choices. Moreover, TMC is expected to gain a higher level of social acceptance than taxes. While under a TMC scheme, everyone has free access to a certain extent of travel (if credits are allocated for free), taxes “price the poor out of the market” (Fleming & Chamberlin, 2011). Moreover, money does not flow from citizens to regulating authorities, and citizens can – if they do not use all their initially allocated credits – even financially benefit from the scheme. Dogterom et al. (2017) conclude that the effectiveness of a TMC scheme in road transport is equal or superior to the effectiveness of other financial incentives with equivalent costs. We argue that there are good reasons to expect that a TMC scheme affecting the aviation sector will be more effective than existing instruments. First, under the EU emission trading system (ETS) airlines can purchase additional emission allowances which leads to an excess of total emissions (van Geuns, 2021). Second, while under ETS the costs for allowances are first paid by the airline and therefore not necessarily fully passed on to the traveler, under a TMC scheme the costs for the internalization of the emission costs are fully borne by the traveler (Krenek & Schratzenstaller, 2017).

2. Research gaps and objective

Past research has hitherto provided limited insights into the impacts of TMC on travelers choices (Dogterom et al., 2017, Provoost et al. 2023) for example in terms of impacts on modal split and trip cancellation. Moreover, the few studies such as those of Aziz et al. (2015), Raux et al. (2015), Dogterom et al. (2018) or Tian et al. (2019), have focused on local implementations and land transport only, i.e TMC applications in the urban mobility context. In contrast, despite the environmental relevance and favorable implementation context (e.g. easier to enforce, fewer actors involved), the application of TMC for long-distance travel has not yet been investigated. We hereby address this research gap.

Our objective is to estimate the impact of a TMC scheme on the modal split for long-distance leisure travel in Europe. Furthermore, we aim to investigate the interaction between travel behavior and credit market behavior and the resulting credit price that will emerge under equilibrium. Thereafter, we will analyze the resulting changes in travel demand patterns, including the potential reduction in overall demand for long-distance leisure travel. We also test for the sensitivity of our findings in relation to a range of values of price elasticity of demand and different developments in the share of electric cars and sustainable aviation fuels. The travel modes considered in this study are air, rail and car.

3. Methodology

3.1. Concept

We envision the introduction of a TMC scheme for long-distance travel at a large geographical scale, such as across Europe. One central authority formed by all participating countries is responsible for the credit supply, for the imposition of credits (re-collecting the credits people spend when travelling) and for the provision of a central credit market where people can trade credits. The proposed scheme allocates credits for free and on an equal basis, i.e. each citizen of all countries within the perimeter receive an equal initial number of credits. Each citizen living in a country within the perimeter of the TMC scheme is a user of the TMC. A user can trade credits and is obliged to pay credits when travelling long-distance by air, rail or car. The number of credits consumed by each long-distance trip is proportional to the amount of CO_2 emissions associated with this trip. The TMC scheme shall apply for leisure trips only because leisure travelers bear the costs themselves, while for business trips the traveler makes the mode choice, but the company pays for it. Moreover, the cost perception for business trips can be distorted as the costs of business travel are subsidized by governments (Leiper, Witsel, & Perry Hobson, 2008). Therefore, the mode choice for leisure trips can be more directly steered by policy instruments directed at individuals.

3.2. Modelling framework

The interactions between travel (mode, route, trip cancellation) choices of individuals and credit market (purchase or sell) choices of individuals are illustrated in Fig. 1. The relation between total credit demand – the total credit expenditure resulting from the collective outcome of individual travel choices – and credit supply – determined by the CO_2 emission reduction target set by the policy maker – drives the credit price. A discrepancy between credit expenditure and credit allocation at the individual level leads at the collective level to changes in credit price. The credit price determines in turn the extent to which travelers are stimulated to shift into more sustainable travel behavior – modal shift, route shift and trip cancellation. The inter-relation between travel decisions and trading decisions constitutes the main feedback loop that drives the market dynamics leading to the emergence of a credit price in equilibrium. The change in travel behavior leads to a change in total CO_2 emissions. This iterative process results in a market equilibrium state, at which the CO_2 emission target is attained.

3.3. Transport supply specifications

The specifications for air, rail and car for travel time and travel cost are illustrated in Fig. 2. Travel times for air and rail consist of access, departure station/airport, in-vehicle and egress times, whereas car travel time corresponds to in-vehicle time only. It is assumed that travelers live in the city center and car travel times between the city center and an airport are used to estimate the access/egress times. Hence, access time to the airport depends on the specific city-airport combination, whereas access time to a train station is set constant at 20 min. The time needed to get from the plane or train to the egress mode is neglected for both train and plane. Air and rail in-vehicle time are specified directly based on the outcomes obtained from travel journey planners (for details see subsection 3.1).

For air and rail travel costs, real-world ticket costs are obtained from travel journey planners. Car travel costs are assumed to be the sum of fuel costs and toll costs, whereas fixed costs are neglected as they are often seen as sunk costs and therefore not considered when people choose a travel mode. Fuel costs are differentiated by country, and it is assumed that half of the fuel is tanked up in the origin

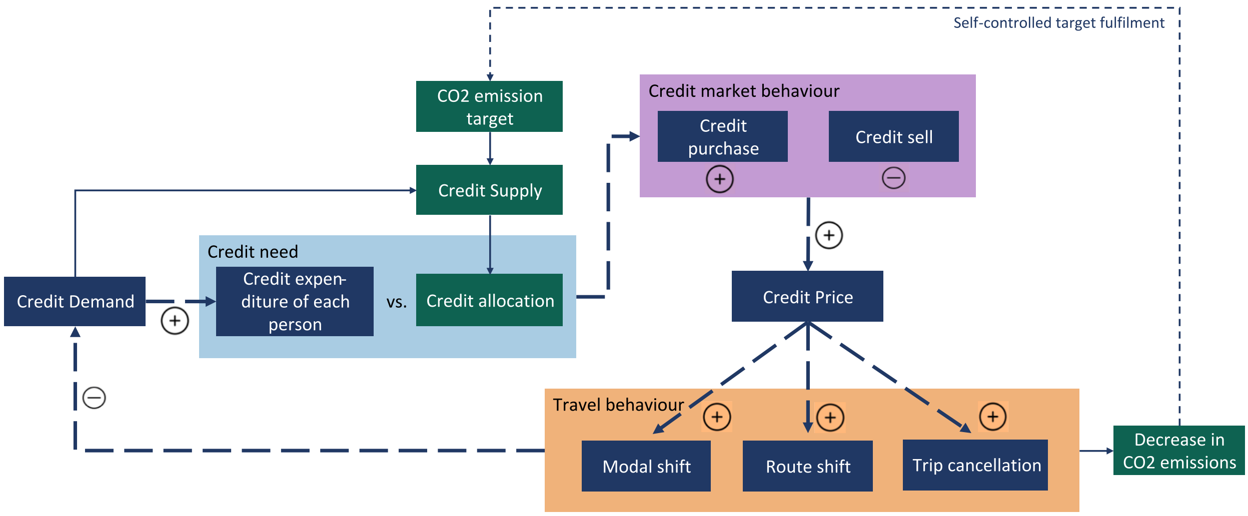

Fig. 1. Interactions under TMC.

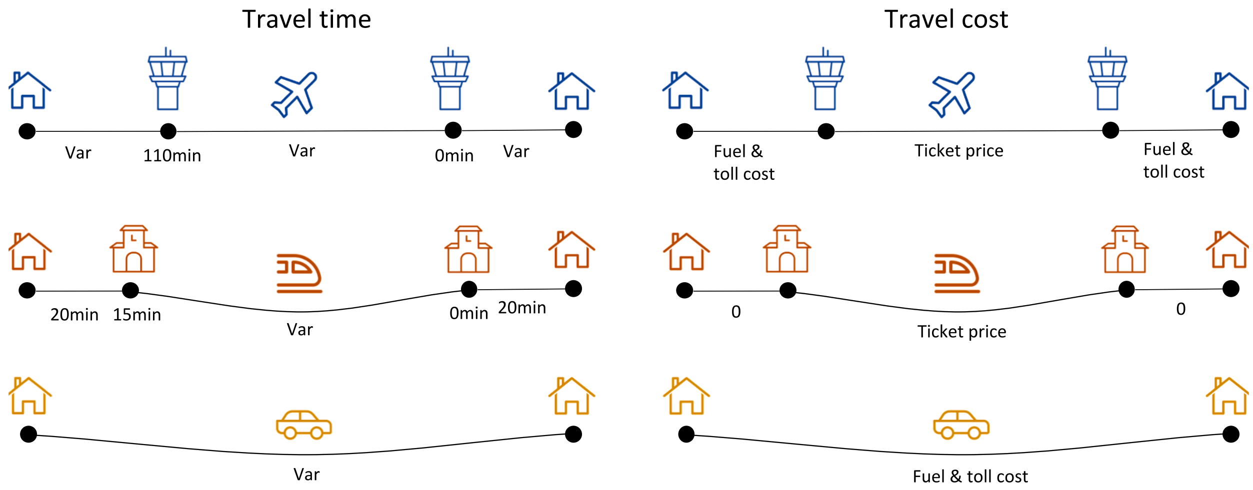

Fig. 2. Mode specifications. Travel time (left), travel cost (right).

country and half in the destination country. The toll cost is set to 0.06€ per km, based on Discover Cars (2021). This calculation is also applied for the access and egress legs of an air travel journey.

In addition to the travel time and cost specifications which traditionally influence individual travel choices, the CO_2 emissions associated with travelling by each mode indirectly influence travelers' choices through their impact on the number of credits charged. The latter has a monetary value that then enters travelers' choice consideration as described in the subsequent subsection. Further specifications for air, rail and car travel for determining the related CO_2 emissions are provided in Table 1. Car occupancy is assumed to be 1.9 for this travel distance and purpose (Reichert et al. 2016 and BFS and ARE 2017). The fuel consumption of a car is set to 7 L per 100 km. The detour factor (deviation from the direct distance) is assumed to be 1.3 for rail travel and 1.2 for car travel according to own estimations. The CO_2 emissions per vehicle and/or passenger-kilometer are derived from Milieu Centraal et al. (2015). Note that for air travel, emissions per passenger-kilometer are assumed to decrease linearly for distances between 400 km and 1,000 km. Since only about 2 % of all the cars in use where electric in Europe as of 2022 (IEA 2023), we apply here the emission values for a combustion engine. Based on these assumptions, air emissions per passenger-kilometer are higher than those for car for flights distances of 900 km or longer.

All airports accessible within an hour from a given origin or destination city are considered feasible options and are assigned to a city. For each OD-pair connection (OD-pair for one travel direction) where a city is involved which has multiple airport options, an airport choice is undertaken. The generalized costs of a trip are computed for each airport pair, including all relevant travel time and cost components as illustrated in Fig. 3. The airport pair for which the generalized costs are the lowest is selected. Fig. 3 shows the airport choice for the feasible airports at the example of the OD-pair connection Amsterdam – Milan (exemplary values).

3.4. *Transport demand specifications*

The TMC scheme impacts the overall demand for long-distance travel as well as the modal split thereof. The trip cancellation rate is calculated for each OD-pair connection and each mode using price elasticity of demand. The elasticity value derived from de Granados et al. (2012) is assumed to be −0.6 for the base case. The new passenger volume is computed for each OD-pair connection using the obtained trip cancellation rate.

To estimate the modal split under a TMC scheme, the costs of the credits needed for a trip are incorporated into the utility function. Eq. (1) shows the calculation of the utility u for mode m for travelling from city i to city j. t stands for travel time, c for travel costs and θ is the value of travel time (VTT).

Table 1
Further mode specifications.

	Vehicle occupancy	Fuel consumption	Detour factor	CO2 emissions per passenger-kilometer			
Air Travel			1.0	<= 400km 0.138[1]	>= 1,000km 0.101[1]	400km – 1,000km 0.138 – 0.101	access & egress 0.107
Rail Travel			1.3	0.017 [1]			
Car Travel	1.9[2]	7lt / 100km	1.2	0.107 (0.204[1] per vehicle-kilometer)			

[1] Milieu Centraal et al. (2024): Indicated values (0.234 for under 400 km and 0.172 for over 1′000 km) divided by 1.7, to obtain pure CO_2 emissions (values indicated in the source include non-CO_2 effects).
[2] BFS and ARE (2017), Reichert et al. (2016).

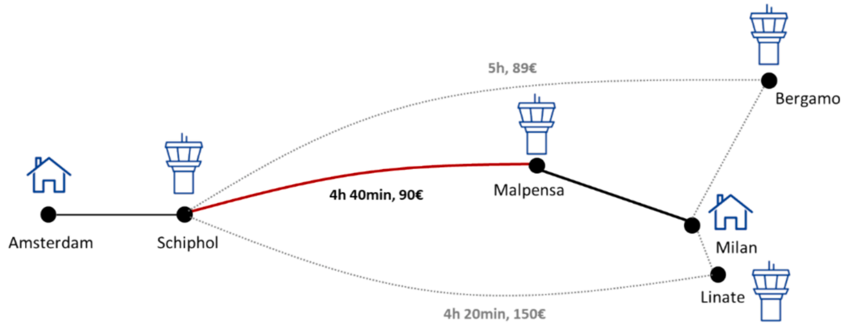

Fig. 3. Airport choice for Amsterdam – Milan.

$$u_{ij,m} = \theta \bullet t_{ij} + c_{ij,m} + p \bullet d_{ij,m} \bullet e_{ij,m} \tag{1}$$

The VTT of an area can be expressed as the GDP of the area divided by the population and the average working hours of the workers in the area (Hu, Duan, & Li, 2022). Hence, the VTT is calculated for each country and adjusted for leisure travel (average of 11.82€ for Europe, according to Wardman et al. 2016). To obtain the VTT per city-pair connection, it is assumed that all travelers between two cities have origin in the countries of these cities and that the share of the traveler's nationality equals the share of the population of the origin and destination country.

The last term in Eq. (1) pertains to the credit costs which equal the credit price, p, times travel distance, d, times emissions per passenger-kilometer, e. Even though credit allocation is free, the credit costs are always added up to the travel costs, as credits could be sold if they were not used. Hence, travelers miss revenue if they use the allocated credits.

Next, the modal share of each mode for each city-pair connection is computed using a Logit model, as indicated in Eq. (2).

$$P_{ij,m} = \frac{e^{U_{ij,m}}}{\sum e^{U_{ij,m}}} \tag{2}$$

The CO_2 emissions of all included trips, E, are then calculated based on the obtained travel flows per travel mode per OD pair as follows:

$$E = \sum_{ij} V_{ij} \bullet (P_{ij,air} \bullet d_{ij,air} \bullet e_{ij,air} + P_{ij,rail} \bullet d_{ij,rail} \bullet e_{rail} + P_{ij,car} \bullet d_{ij,car} \bullet e_{car}) \tag{3}$$

where V_{ij} is the travel flow from city i to city j and $e_{ij,m}$ is the amount of emissions associated with travelling from city i to city j using travel mode m.

3.5. Credit price dynamics

The total credit supply is determined by scaling down the total emissions generated by the current credit demand (CO_2 emissions of all included trips) based on the emission reduction target. Credit allocation, which is the same for all citizens, equals the total credit supply divided by the number of citizens living within the perimeter. The income elasticity of long-distance travel demand is used to assess the differences in credit expenditure between citizens of different countries and is set to 1.4 (Christensen & Nielsen, 2018). Consequently, there are countries with citizens with a credit shortage (positive credit need) and countries with citizens with a credit surplus (negative credit need). In each iteration of the feedback loop shown in Fig. 1 a new credit price prevails based on the relation between credit demand and credit supply and individuals make new travel and TMC market decisions.

The credit price reaches its equilibrium state when the sum of credit needs of all citizens is zero, i.e. everyone is content with the number of credits they have and no one is interested in either buying or selling credits. The credit price increases if that sum is above zero (credit request higher than credit availability in the market) and decreases if it is below 0 (request lower than availability). We hence assume that the market clears at all times, i.e. all credits on the market are always traded so that there are no leftover credits on the market. We define an equilibrium state as one where the credit price of the current iteration differs by less than 1 % from the one attained in the previous iteration.

4. Application, results and discussion

4.1. Case study description

We apply a TMC scheme for the geographical area spanning the European mainland and the United Kingdom. Considering the "2030 Climate target plan" and assuming a linear decrease, the CO_2 emissions reduction target is set to 30 % for the study year 2023 (European Commission, 2020). A selection of 73 main metropolitan areas to represent the European Network is adopted from Donners

(2016). To obtain the selection of airports which are to be assigned to the selected cities, data from Grolle (2020) is used. A web scraping script is developed in PyCharm to obtain ticket prices for air and rail travel. The booking platform kiwi.com is used for flight ticket prices and trainline.com for rail ticket prices. For trainline.com, the first 8 options are saved and the one with the lowest generalized cost is chosen. Finally, it results in 307 million trips performed between 2,998 OD-pair connections included in our case study. Fig. 4 shows the cities included in the case study and number of OD-pair connections per city. All model runs are performed in PyCharm, using the pandas library. The running time of the script to calculate the modal split and the modal shift is a matter of minutes when run on a standard PC. Model outputs are available on a public repository (Tanner and Provoost, 2023).

4.2. Results and discussion

In our discussion of the results, we first present the evolution of the credit price under different emission reduction targets throughout model iterations and the resulting equilibrium state (3.2.1). Then we turn to analyzing the overall impacts of the TMC scheme on modal split referred to number of trips and trip cancellation (3.2.2). Thereafter the impacts on a selected set of city-pairs are illustrated, followed by the analysis of the geographical disparities of the impacts of the TMC scheme (3.2.3).Last, we conduct a sensitivity analysis for the price elasticity of demand and different technological developments (3.2.4).

4.2.1. Credit price evolution

Fig. 5 provides insights into the evolution of the credit price (left) and the emission change (right) for 20 model iterations until an equilibrium state is obtained. The credit price that emerges in the market for an emission reduction target of 30 % is found to be 272€ per ton of CO_2. We also test the equilibrium results for different reduction targets and find that up to a target of 80 % the credit price increases approximately linearly. Higher reduction targets result in a drastic increase in the credit price as shown in Fig. 6. In the remaining of our analysis, we proceed with the analysis of the TMC scheme designed to lead to an emission reduction of 30 %.

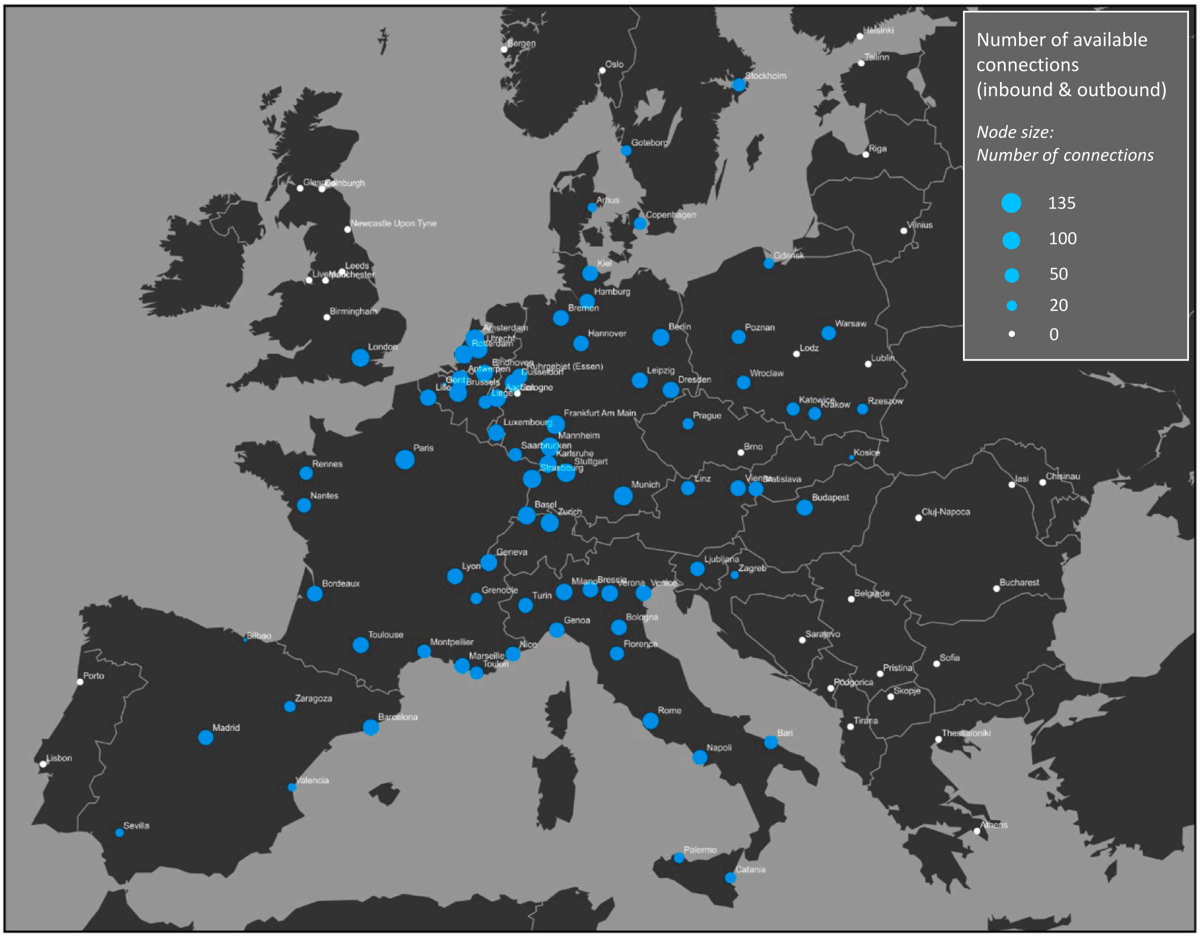

Fig. 4. Number of OD-pair connections per city included in the case study.

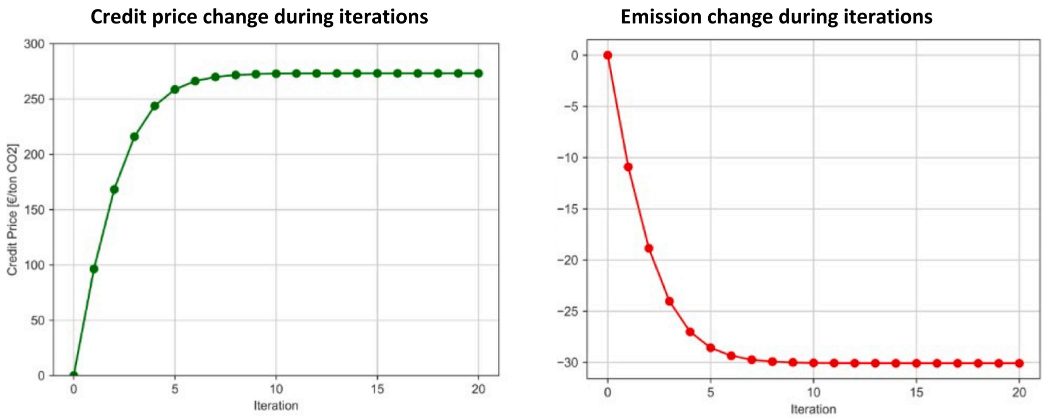

Fig. 5. Evolution of the credit price (left) and the emission change (right) during 20 iterations.

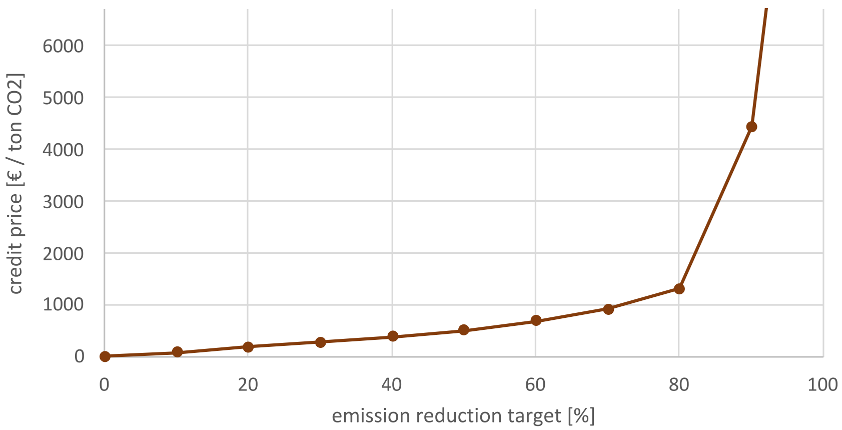

Fig. 6. Equilibrium credit price depending on emission reduction target.

4.2.2. Overall impacts of the TMC scheme on modal split and trip cancellation

The 30 % emission reduction is achieved by means of both trip cancellation and modal shift. In other words, the TMC leads to fewer long-distance trips being performed and those performed are shifting towards less polluting modes of travel. Fig. 7 shows the modal split referred to number of trips (averaged over all OD-pair connections and weighted by passenger volume). On the left, the situation without TMC and on the right the situation with TMC are shown. In the absence of a TMC scheme, 50 % of the trips are undertaken by air, 23 % by rail and 27 % by car. Under a TMC scheme, of those trips that are performed, air travel holds 42 %, rail travel 32 % and car

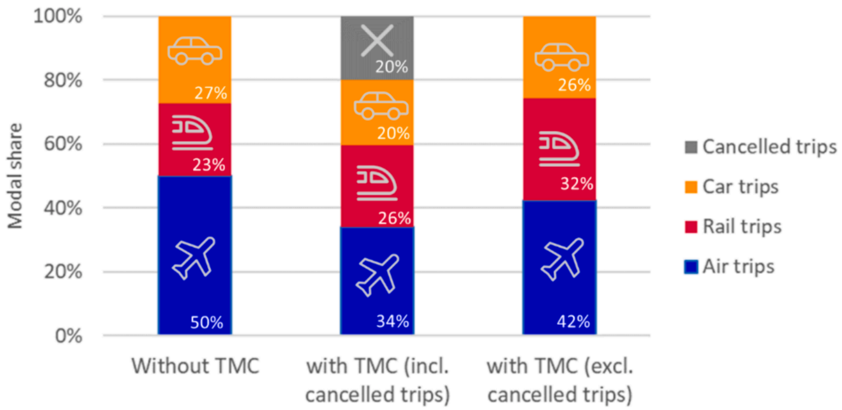

Fig. 7. Average modal shares without and with TMC.

travel 26 %. Hence, there is a modal shift away from air travel of 8 %, towards rail travel of 9 % and away from car travel of 1 %. The share of cancelled trips amounts to 20 %, amounting to 61million trips for our study year. When including the cancelled trips in the modal split, air holds 34 %, rail 26 % and car 20 % (see numbers in Fig. 7).

To better understand the variation in the modal shift induced by the introduction of TMC among city-pair connections, we display in Fig. 8 the distribution of the incurring modal shift caused by TMC for each mode using a violin plot. Air modal shift is in almost all cases negative. Rail modal shift is in all cases positive, i.e. travelers shift towards rail in the presence of a TMC scheme. Car modal shift is in nearly all cases negative. A closer inspection reveals that on the one hand, car modal share increases on a few certain OD-pair connections which are short routes of up to 900 km and for which air emissions are higher than car emissions (see Table 1). Examples of which are the OD-pairs of Berlin – Essen and Dusseldorf – Arhus. On the other hand, air modal share increases on a few long OD-pair connections for which air emissions are lower than car emissions and for which there is no suitable rail alternative. This is the case for example for the OD pairs of Florence – Poznań and Gothenburg – Luxembourg.

Since the competitive position of each of the travel modes considered depends on the travel distance − due to relations between costs and variable time components and distance, as well as the fading relative impact of fixed time components with increasing travel distance − we investigate how the modal shift observed varies as a function of travel distance. Fig. 9 shows the impact of the TMC on the modal split as a function of travel distance. The curves show the average modal shares as a function of distance between traveler's origin and destination, based on a third-degree polynomial regression of the OD-pairs connection data. The curves show that under a TMC the share of rail travel increases by 10 percentage points for mid-range distances of 500–800 km.

While Fig. 9 is not weighted by the corresponding passenger volume per travel distance category, we are also interested in the change in travel demand per mode for different distance ranges in absolute terms. Fig. 10 shows the third-degree polynomial regression of the passenger volumes of each OD-pair connection for each mode in both the initial state as well as under the TMC, as a function of distance between traveler's origin and destination. For air, travel demand reduction is the largest of all modes, in line with the aggregate results reported in Fig. 7. For example, demand for flights of 1000 km by one third from 60,000 to 40,000 passengers. It can be observed that the longer the travel distance – and thereby the more credits are charged − the larger is the reduction in air passenger volumes due (almost entirely) to trip cancellation.

The observed modal shifts and changes in passenger volumes are driven by the underlying credit prices which reflect the trade-offs travelers make between travel preferences and monetary considerations which are ultimately reflected in both travel choices and trading choices. Fig. 11 shows the credit cost distribution of all included trips per mode. The credit costs are lowest for rail travel. While median credit costs for air and car travel are comparable, mean credit costs are higher for car travel due to the longest distance trips which are associated with higher credit costs for car than for air. Under the found credit price of 272€ per ton of CO_2 (3.2.1), the credit costs for e.g. a trip from Amsterdam to Zurich are 21€ when travelling by plane, 4€ when travelling by train and 24€ when travelling by car. Generally, also the percentual increase of monetary costs is highest for air and car and lowest for rail travel. For low-cost flights, the credit costs often exceed the monetary travel costs.

4.2.3. Geographical variability in the impacts of the TMC scheme

It is evident from the results presented above that the impact of the TMC scheme varies across city-pair connections. Fig. 12 shows a ternary plot for a selected set of city-pair connections, displaying the modal shift induced by the TMC for selected origin–destination combinations. The dot size is proportional to the magnitude of passenger flow per direction per year and the dot color stands for the (direct) trip distance. For instance, on the Paris-Madrid connection, air travel has a monopoly. The TMC scheme hardly induces a modal shift towards rail and car. However, every fourth trip is cancelled (not shown in the figure). In contrast, the TMC scheme strongly affects the market shares of different modes in the Amsterdam-Berlin case. The inclusion of credit costs increases the

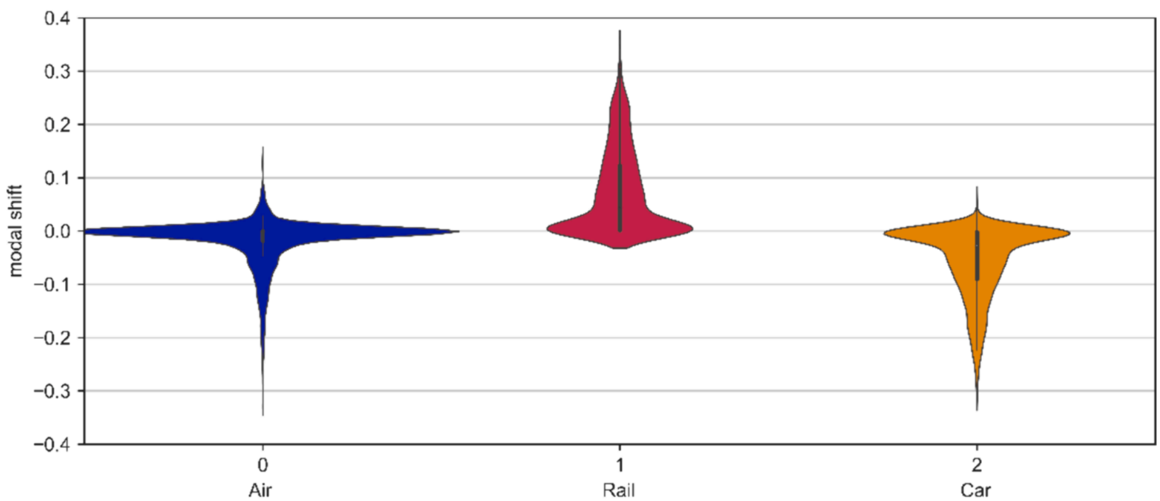

Fig. 8. Modal shift distribution per mode.

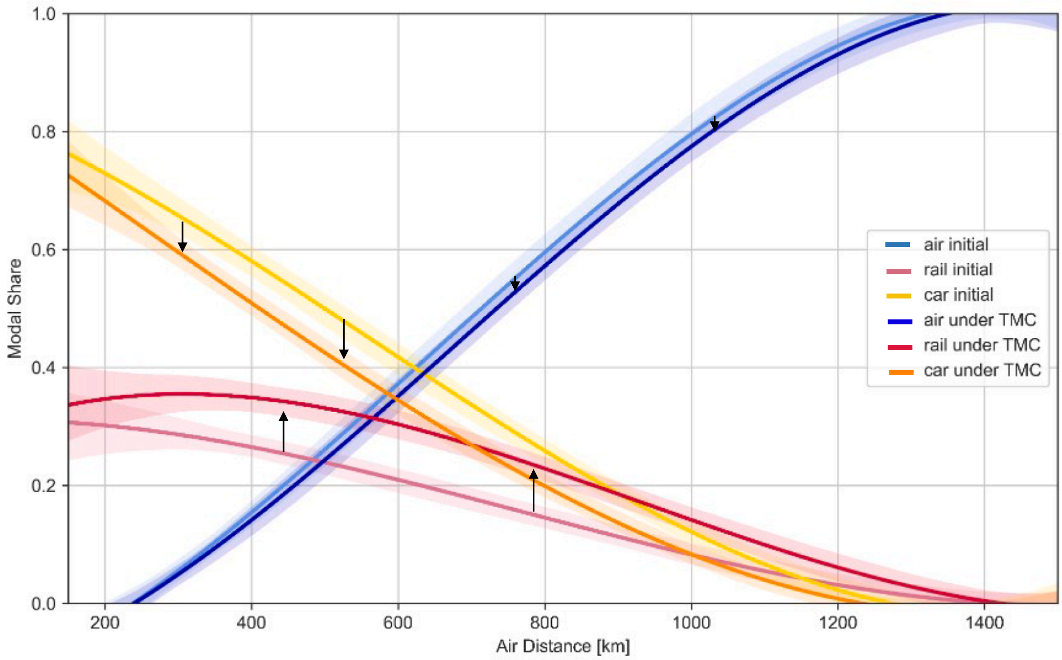

Fig. 9. Modal shares without and with TMC as a function of direct distance. Regression of 3rd-degree polynomial of all OD-pair connections.

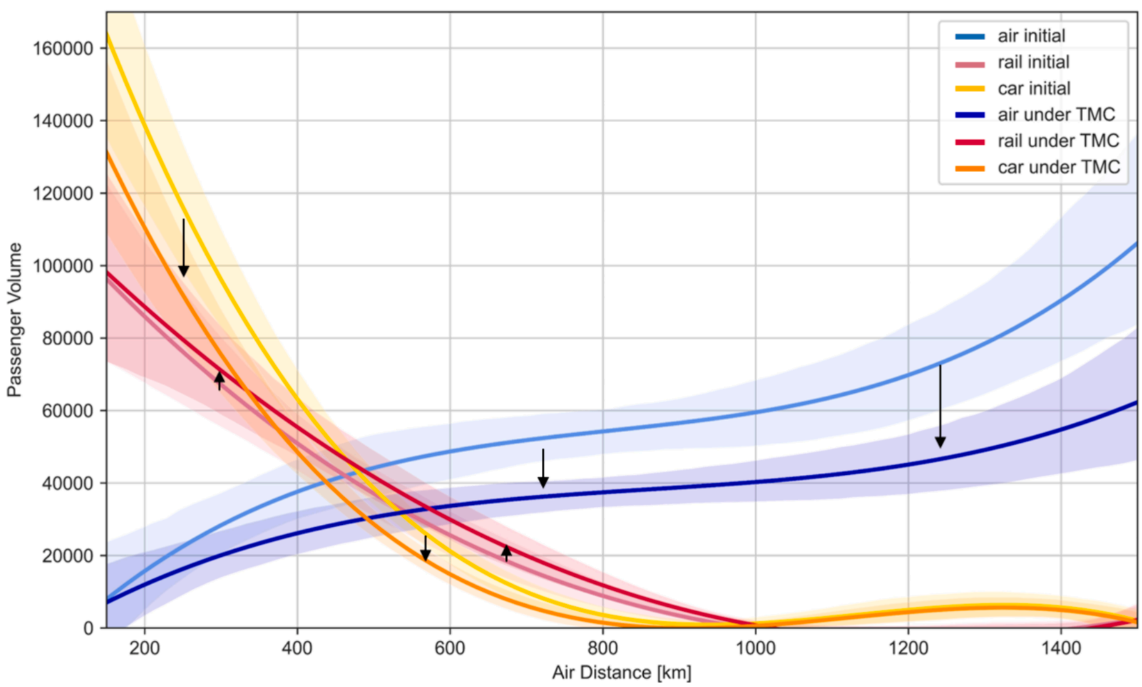

Fig. 10. Passenger volume per mode without and with TMC as a function of direct distance. Regression of 3rd-degree polynomial of all OD-pair connections.

competitiveness of rail, and a substantial share of travelers shifts from air to rail. Furthermore, rail is predominant on the Madrid-Barcelona, Zurich-Paris and Berlin-Munich connections, which is due to the availability of a high-speed train connection. Consequently, the share of rail is already relatively high to start with and further increase in the presence of a TMC scheme. In contrast, the market share of rail is and remains with the TMC low on the Budapest-Prague connection despite the relatively short distance since

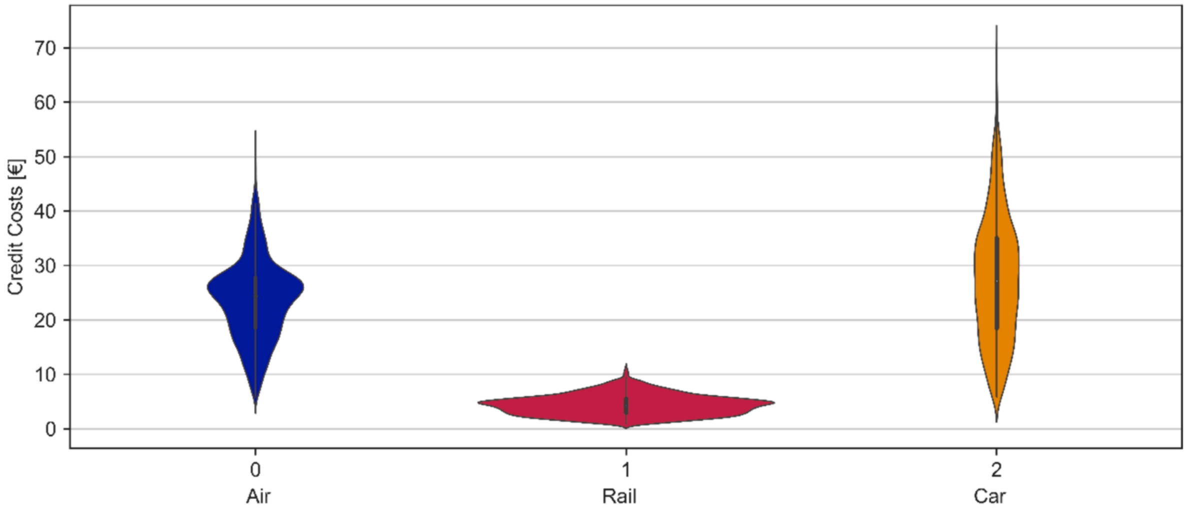

Fig. 11. Credit cost distribution per mode.

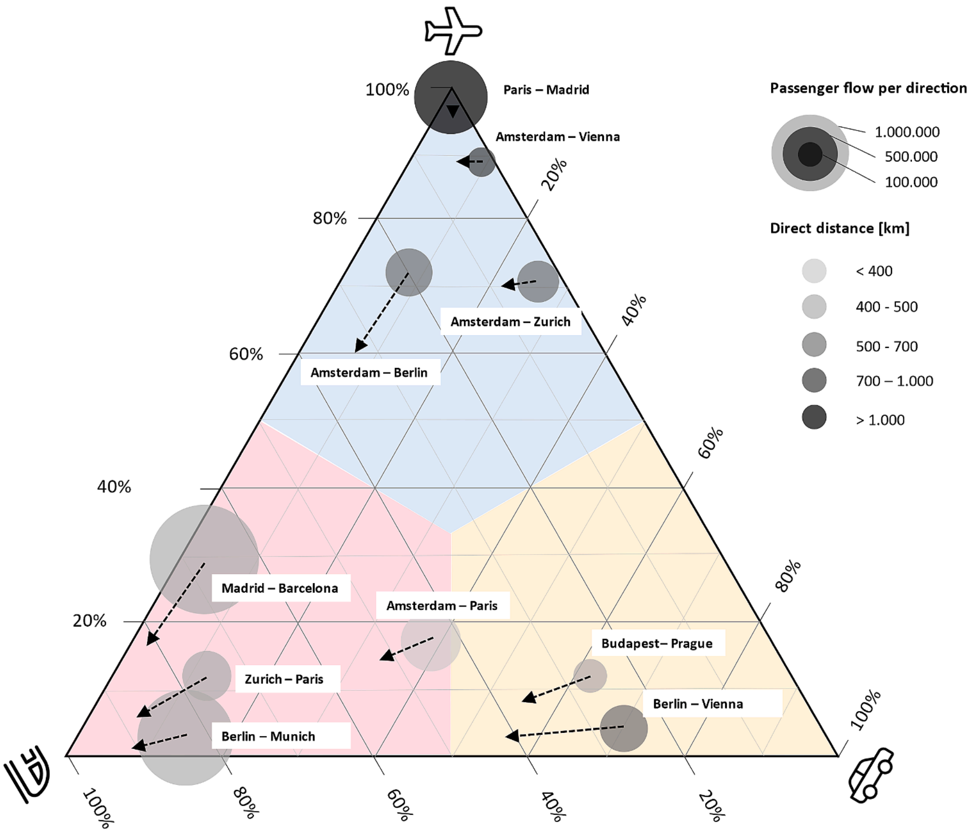

Fig. 12. Ternary plot of the modal shift due to the TMC for selected city-pair connections.

travel speed is relatively low. Car remains the main travel mode for this connection as rail is still not a strong competitor. Generally, it can be observed that medium-distance trips (500–700 km) tend to have the highest modal shifts (due to strong competition between modes).

Next, we turn into analyzing the geographical disparities of the TMC scheme impacts by investigating which OD-pair connections are most affected. Fig. 13 shows all OD-pair connections with an air modal share decrease of more than 10 %, corresponding to 6 % of all OD-pair connections. The color range of the edges represents the modal share of air travel under TMC. Medium-distance connections dominate this chart. Arguably, these city-pair connections have a very competitive market which leads to none of the transport modes dominating the market. This can be observed by the color of the edges – these OD-pair connections are characterized by having neither a very high nor a very low air modal share and are therefore depicted in light red. Consequently, a small change in travel costs due to the introduction of credit costs is sufficient for inducing a large behavioral response in the form of modal shift. In contrast, the impact of the TMC on the modal split is relatively small for either very long or very short connections, as rail is often not competitive or already holds a large modal share, respectively. Furthermore, Fig. 13 shows that cities in central-eastern European countries have a high relative occurrence, which means that they are the origin or destination of many OD-pair connections for which the share of air travel is significantly reduced. Travelers from these countries have a comparatively lower value of travel time. Consequently, they rather accept longer travel times than higher travel costs, and therefore are more inclined to opt for the train or the car over the plane in the presence of a TMC scheme.

Fig. 14 shows all OD-pair connections with an air trip cancellation rate of more than 50 %, corresponding to 4 % of all OD-pair connections. The color range of the edges represents the initial modal share of rail travel. As can be seen, these OD-pair connections are characterized by a very low rail modal share (edges are mostly displayed in white). Upon further investigation we observe that the vast majority of the trips amongst these OD-connections is performed by air, and in particular low-cost flights. Consequently, the introduction of the TCM scheme leads to a high relative increase in travel costs. Cities at the edge of our case study area, whose share of long-distance connections is high (Southern Italy, Spain, Poland), are amongst those most affected. In contrast, low trip cancellation rates occur on OD-pair connections with a high initial modal share of rail.

4.2.4. Sensitivity analysis

Given the wide range of values reported in the literature for the price elasticity of demand, we test for lower and higher elasticity values, i.e. e = -0.35, e = -0.85 and e = -0.1 (−0.6 in the base case). Fig. 15 shows the resulting credit price under these values. The weaker the elasticity, the more travelers do not want to reduce travel and are therefore forced to shift modes because their credits become a scarcer resource. The credit price ranges from 159€ to 424€, for price elasticities of −1.1 and −0.35, respectively.

Fig. 16 shows the difference in the modal shares for the three tested price elasticity values presented in relation to the reference value of −0.6 (base case). For e = -0.35, the share of air travel remains nearly unchanged, whereas the share of rail travel increases by 3.5 percentage points and the share of car travel decreases by 1.3 percentage points. The share of cancelled trips decreases by 2.3 percentage points. For e = -0.85 and −1.1, modal shift trends are the other way around: Increasing car share and cancelled trips and decreasing rail share. A stronger elasticity leads to a higher trip cancellation rate, hence modal shift away from car and towards rail is reduced since more credits are available for those still traveling.

To test for the sensitivity for technological progress, we create two additional scenarios for 2030. The scenarios reflect medium technological progress and high technological progress regarding the composition and efficiency of transport vehicle fleets. For the first, the share of electric cars is assumed to be 25 % and the share of sustainable aviation fuels is assumed to be 5 % (Shehab et al. 2023 concluded that 4.8 % is the expected capacity of sustainable aviation fuels in the EU in 2030). The high technological progress scenario reflects to a reality where 50 % of the car fleet is electric (forecasts reported in IEA 2023 put this share between 40 and 70 %) and the share of sustainable aviation fuels amounts to 15 %. Emissions of electric cars are assumed to be a third of emissions of conventional cars (Milieu Centraal et al., 2024), and emissions of sustainable aviation fuels are assumed to be 80 % lower than the ones of conventional fuel (IATA, 2023). Rail emissions are identical for all scenarios. Table 2 gives an overview of the emissions depending on the scenario which the reader may contrast with those reported for the base case scenario in Table 1.

To control for the impact of technological progress, we test for the case that such progress is made with and without the introduction of TMC. Since we find that in the absence of TMC modal shares under the medium and high technological progress scenarios are overall comparable to those obtained in the base case (differences below 2 %), we report in the following the results for the case where those occur in conjunction with TMC. Fig. 17 shows the average modal split referred to number of trips for the situation without TMC and for the three emission scenarios with TMC. Technological progress will contribute to achieving the required emission reduction of 30 %, thereby mitigating the extent of behavioral change. The credit price decreases to 235€ in the medium scenario and decreases further to 164€ in the high scenario. Compared to the base case, the main modal split difference caused by greater technological progress are observed in the shares of air travel, car travel and cancelled trips. In the medium scenario, the share of air travel is two percentage points higher, the share of car travel three percentage points higher and the share of cancelled trips is four percentage points lower than in the base case. For the high scenario, it is + 7 (from 34 to 41 %), +5 (from 20 to 25 %) and −10 (from 20 to 10 %) percentage point changes, respectively. Fast progress in reducing the emissions generated by car and air travel result in tempering the modal shift away from these modes when TMC is introduced.

5. Conclusion

The proposed Tradable Mobility Credit Scheme offers a potentially effective policy instrument for achieving the GHG emission reduction goals. We estimated the impact of a TMC scheme on the modal split and trip cancellation for long-distance leisure travel in Europe. With a TMC scheme applied for a large part of the European continent, the credit price that will emerge in the market is found to be 272€ per ton of CO_2, assuming an emission reduction target of 30 %. This carbon price is higher than the values estimated by Kaufmann et al. (2020), by simulating economic and energy systems in a “near-term to net zero approach”. Assuming that carbon pricing plays a role as a major decarbonization tool, they found that the carbon price has to be set to 120€ per ton CO_2 in 2030 in order to attain the 1.5° C goal. The discrepancy between the two credit estimates might be explained by the scope of the studies – while Kaufmann et al. (2020) incorporated all sectors, this study estimated the carbon price for only part of the transport sector. It is known

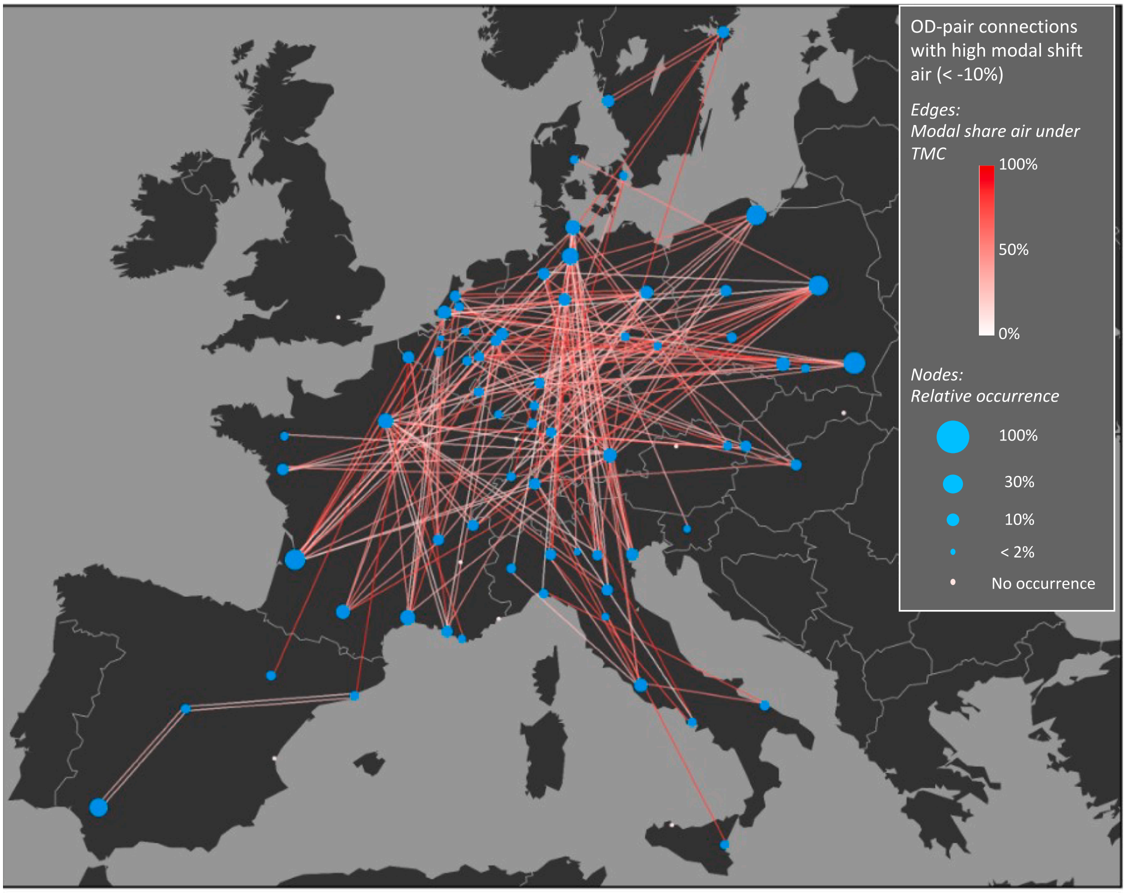

Fig. 13. OD-pair connections with a high modal shift away from air (<-10 %). Edge color: Modal share air under TMC. Node size and color: Relative occurrence per city.

that decarbonization in long-distance transport is more challenging than in other sectors. Hence, it is reasonable that our estimated carbon price is higher. Otherwise, the attained travel behavioral changes would not be sufficient. Modal shift and trip cancellation rate mostly depend on the local value-of-time and the extent of modal competition. The TMC scheme causes a shift of 8 percentage units away from air, a shift of 9 percentage units towards rail and a shift of 1 percentage unit away from car in our analysis. The total reduction in the number of trips performed amounts to 20 %. We observe some geographical disparities with those residing at the edge of our analysis area being most likely to cancel their trip due to the absence or limited rail alternatives combined with a lower than average value of time.

The perimeter of the TMC scheme was limited in this analysis to the mainland of Europe and the United Kingdom. Hence, credit costs can be circumvented by choosing an intercontinental destination instead of a European one, i.e. an undesired increase in emissions resulting from trip destination shifts. Further research could examine the consequences of extending the perimeter of the TMC scheme. Including long-distance bus (coach) travel would have provided a more complete picture of the impacts of the TMC scheme, especially for city-pair connections where rail is not available or rail travel times are excessively long. Moreover, business travelers shall also be included and distinguished in terms of their travel preferences and value-of-time considerations. Our study did not consider the non CO_2-effects from aviation, mainly caused by contrails and cirrus clouds. The GWP100 (Global Warming Potential with a 100-year horizon) is 1.7 times as high for CO_2 emitted during the cruise phase than on the ground, due to the altitude (Åkerman et al., 2021). Since we focus on the relative reduction of CO_2 in this study, the non-CO_2 emissions would be cut to about the same extent with the deducted credit price. Including non CO_2-effects would lead to a higher reduction of air travel and stronger shift towards rail and car travel. It should be noted that those travelers who cancel their trip make a financial gain because they can sell the credits they would have otherwise used for performing the trip. For example, someone who decides not to fly from Rome to Amsterdam can earn 37€. Whether this is desirable from a societal perspective depends on the wider economic benefits associated with the intended trips (e. g. contribution to local economy, missed business opportunities). Further research may aim at quantifying and incorporating such benefits. Next to modal shift and trip cancellation, future studies may also include potential impacts on destination choice and thereby trip distribution as well as additional determinants of travel choices such as mode-specific preferences and transfers. In addition, extending the model to consider market dynamics will allow treating (air and rail) ticket prices as endogenous rather exogenous variables with ticket prices determined based on revenue management practices.

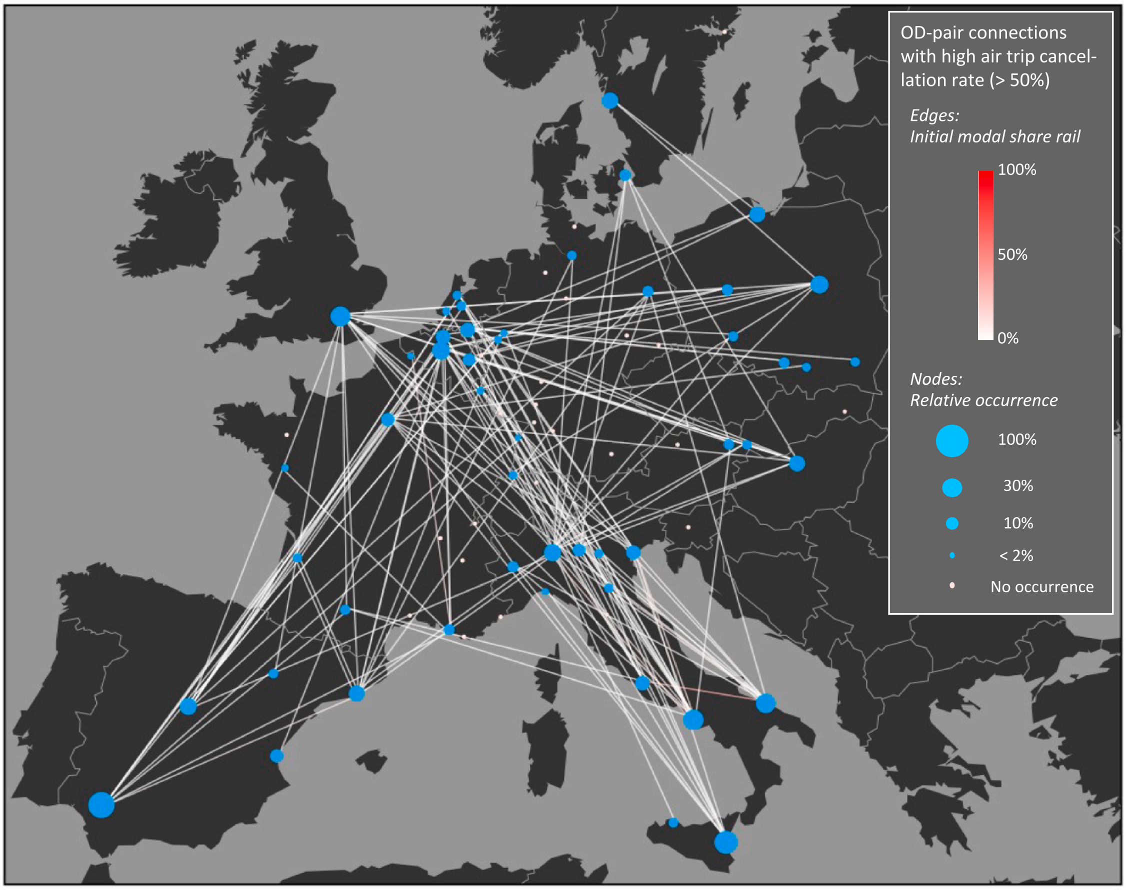

Fig. 14. OD-pair connections with a high air trip cancellation rate (>-50 %). Edge color: Initial modal share rail. Node size and color: Relative occurrence per city.

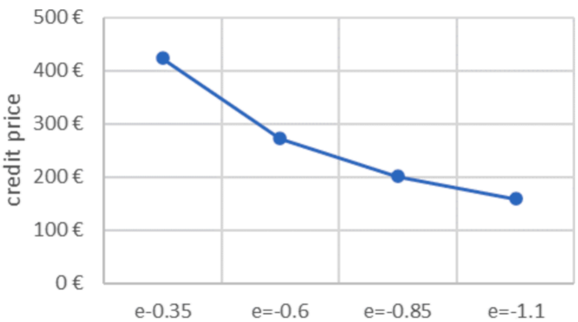

Fig. 15. Credit price under different values for price elasticity.

The results of our work contribute to the on-going debate surrounding instruments for stimulating sustainable (im)mobility, in particular in the context of the long-distance travel market. TMC constitutes a demand management scheme for attaining a policy target. A uniform and free credit allocation, as specified in this study, implies that this is achieved without inducing additional travel costs or implying the transfer of money from citizens to governments or vice-versa. When the amount of credits consumed per travel choice is determined by the respective amount of emissions as specified in this study, then the externalities associated with these emissions are internalized by travelers based on the price that prevails in the market (rather than by a price tag set by the authorities). Travelers that pollute more – because they travel more frequently, longer distances and more often by plane – will consume more credits and are likely to buy credits from those that travel less frequently, shorter distances and more frequently by train. Different values of times mean that some travelers rather sell their credits than consume them. Authorities may want to consider catering for inequality emerging from geographical disadvantages. Finally, an investment in the quality of the rail alternative supply – more direct,

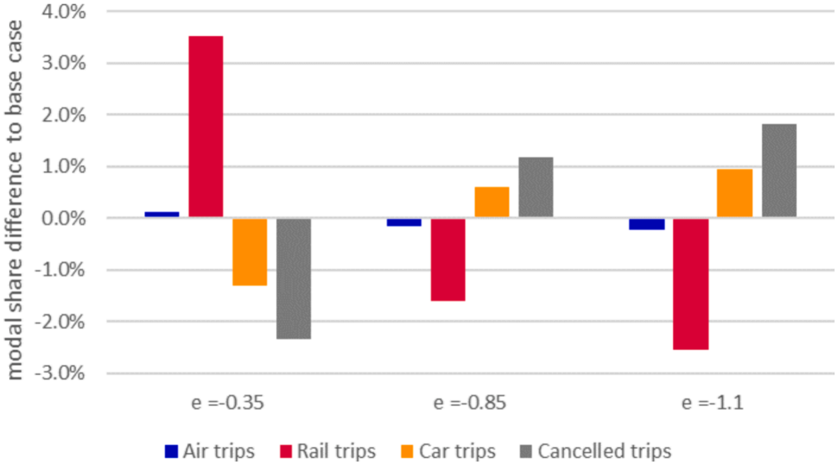

Fig. 16. Credit price under different price elasticity values.

Table 2
Technological progress scenarios – emissions in kg CO_2 per passenger-kilometer.

	Low scenario (base case)	Medium scenario	High scenario
Air Travel	<= 400 km: 0.138 >= 1,000 km: 0.101 400 – 1,000 km: 0.138 – 0.101	<= 400 km: 0.132 >= 1,000 km: 0.097 400 – 1,000 km: 0.132 – 0.097	<= 400 km: 0.121 >= 1,000 km: 0.089 400 km – 1,000 km: 0.121 – 0.089
Rail Travel	0.017	0.017	0.017
Car Travel	0.107	0.089	0.071

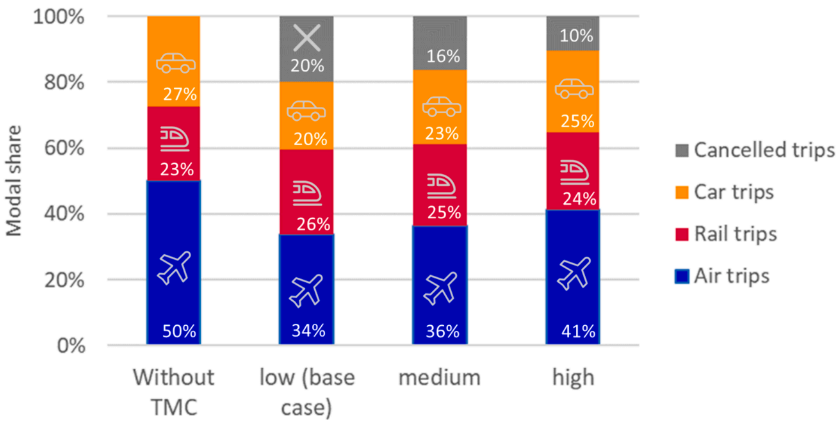

Fig. 17. Average modal shares without and with TMC for the technological progress scenarios.

faster and higher capacity connections – would increase the effectiveness of demand management schemes aimed at modal shifts towards rail, which would decrease the trip cancellation rate and therefore increase social welfare. Investments should be prioritized on medium-distance connections, where the market is most competitive. Such changes in transport supply can be accounted for in applications of the model to future target years (e.g. 2050).

CRediT authorship contribution statement

Sandro Tanner: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Jesper Provoost:** Supervision, Methodology, Conceptualization. **Oded Cats:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

Model outputs are available on a public repository (Tanner and Provoost, 2023). Available at 10.4121/22202389.v1

Acknowledgements

The second and third authors performed this work as part of the DIT4TraM project, which has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement no. 953783.

References

Åkerman, J., Kamb, A., Larsson, J., Nässén, J., 2021. Low-carbon scenarios for long-distance travel 2060. Transportation Research Part D 99, 103010.

Aziz, H.M.A., Ukkusuri, S.V., Romero, J., 2015. Understanding short-term travel behavior under personal mobility credit allowance scheme using experimental economics. Transportation Research Part D 36, 121–137.

BFS, & ARE. 2017. Verkehrsverhalten der Bevölkerung 2015. Neuchâtel: Bundesamt für Statistik, Bundesamt für Raumentwicklung.

Bleijenberg, A. 2020. Air2Rail, Reducing CO2 from intra-European aviation by a modal shift from air to rail. Delft.

Discover Cars. 2021. Toll roads, bridges, and tunnels around Europe. https://www.discovercars.com/blog/tolls-europe.

Milieu Centraal, Stimular, SKAO, & Rijkswaterstaat. 2024. CO2 emissiefactoren. https://www.co2emissiefactoren.nl/wp-content/uploads/2024/02/CO2-emissiefactoren_2024-dd-15-2-2024.pdf.

Christensen, L., & Nielsen, O. A. 2018. What do Europen tourism demand survey tell about long distance travel? Presented at the Transport Research Board, Lyngby: Technical University of Denmark, DTU Management Engineering.

Denstadli, J.M., Veisten, K., 2020. The flight is valuable regardless of the carbon tax scheme: A case study of Norwegian leisure air travelers. Tourism Management 81.

Dogterom, N., Ettema, D., Dijst, M., 2017. Tradable credits for managing car travel: A review of empirical research and relevant behavioural approaches. Transport Reviews 37 (3), 322–343.

Dogterom, N., Ettema, D., Dijst, M., 2018. Behavioural effects of a tradable driving credit scheme: Results of an online stated adaptation experiment in the Netherlands. Transportation Research Part A 107, 52–64.

Donners, B. J. H. F. 2016. Erasing Borders, European Rail Passenger Potential. Master Thesis, Delft: Delft University of Technology.

European Commission. 2020. The 2030 Climate target plan. Communication paper no. COM(2029 562 Final, Brussels: European Union.

European Environment Agency. 2021. EEA greenhouse gases—Data viewer. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

Fleming, D., & Chamberlin, S. 2011. TEQs Tradable Energy Quotas, A Policy Framework for Peak Oil and Climate Change. London: The All Party Parliamentary Group on Peak Oil (APPGOPO) by THE LEAN ECONOMY CONNECTION.

Granados, N., Kauffmann, R., Lai, H., Lin, H., 2012. À la carte pricing and price elasticity of demand in air travel. Decision Support Systems 53 (2), 381–394.

Grolle, J. 2020. A Unified Design of the European High-Speed Rail Network. Impacts of Design, Pricing and Governance Strategies. Master Thesis, Delft: Delft University of Technology.

Hu, X., Duan, J., Li, R., 2022. Research on High-Speed Railway Pricing and Financial Sustainability. Sustainability 14 (3), 1239.

IATA. 2023. Net zero 2050: sustainable aviation fuels. https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet—alternative-fuels/.

IEA. 2023. Electric vehicle sales shares by mode in Europe, 2030. https://www.iea.org/data-and-statistics/charts/electric-vehicle-sales-shares-by-mode-in-europe-2030.

Kaufmann, N., Barron, A.R., Krawczyk, W., Marsters, P., McJeon, H., 2020. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. Nature Climate Change 10, 1010–1014.

Krenek, A., Schratzenstaller, M., 2017. Sustainability-oriented tax-based own resources for the European Union: A European carbon-based flight ticket tax. Empirica 44 (4).

Leiper, N., Witsel, M., Perry Hobson, J.S., 2008. Leisure travel and business travel: A comparative analysis. Asian Journal of Tourism and Hospitality Research 2 (1).

Petersen, M.S., Sessa, C., Enei, R., Ulied, A., Larrea, E., et al. 2009. TRANSvisions, Contract A2/78-2007: Report on Transport Scenarios with a 20 and 40 Year Horizon. Final Report, Project funded by the European Commission - DG TREN.

Provoost, J., Cats, O., Hoogendoorn, S., 2023. Design and Classification of Tradable Mobility Credit Schemes. Transport Policy 136, 59–69.

Raux, C., Croissant, Y., Pons, D., 2015. Would personal carbon trading reduce travel emissions more effectively than a carbon tax? Transportation Research Part D 35, 72–83.

Reichert, A., Holz-Rau, C., Scheiner, J., 2016. GHG emissions in daily travel and long-distance travel in Germany – Social and spatial correlates. Transportation Research Part D 49, 25–43.

Rich, J., Lindhard, S., 2012. A long-distance travel demand model for Europe. European Journal of Transport and Infrastructure Research 12 (1), 1–20.

Shehab, M., Moshammer, K., Franke, M., Zondervan, E., 2023. Analysis of the Potential of Meeting the EU's Sustainable Aviation Fuel Targets in 2030 and 2050. Sustainability 15 (12), 9266.

Tanner S. and Provoost J. (2023). Tradable mobility credits for long-distance travel in Europe – Impacts on the modal split between air, rail and car. Available at https://doi.org/10.4121/22202389.v1.

Tian, Y., Chiu, Y.-C., Sun, J., 2019. Understanding behavioral effects of tradable mobility credit scheme: An experimental economics approach. Transport Policy 81, 1–11.

van Goeverden, C.D., 2009. Explaining Factors for Train Use in European Long-Distance Travel. Tourism and Hospitality Planning & Development 6 (1), 21–37.

Wardman, M., Chintakayala, V.P.K., de Jong, G., 2016. Values of travel time in Europe: Review and meta-analysis. Transportation Research Part A 94, 93–111.