Tradable Mobility Credits for Long-Distance Travel in Europe – Impacts on the Modal Split between Air, Rail and Car

Master Thesis

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Preface

When I was small, my dream was to become a train driver. Later, aviation became my big ambition, and I was almost about to start the airline pilot school. Meanwhile, my life journey has changed, but my passion for transport has stayed. Therefore, I am grateful to write my master thesis in the field of long-distance travel. This thesis marks the end of my master's studies Spatial Development and Infrastructure Systems at ETH Zurich. The semester before writing the thesis I had the great opportunity to do an exchange semester in the master's studies Transport, Infrastructure and Logistics at TU Delft. The city of Delft, all the people I met and the university itself convinced me so much that I decided to stay in Delft for writing my thesis.

I want to express my gratitude to my thesis committee members Prof. Dr. Oded Cats, Jesper Provoost and Prof. Dr. Francesco Corman. Thank you, Oded, for your support, from specifying the topic in the very beginning to the frequent meetings with valuable inputs, always bringing a positive, motivating attitude. Jesper, thank you for your large effort to closely guide me along the whole process, the patience to answer all my questions and for always keeping me on the right path. Francesco, thank you for the supervision from ETH Zurich side with your inputs despite the geographical distance and the examination.

Only because of Oded Cats' and Francesco Corman's support it was possible to write my thesis at TU Delft. I am extremely grateful and would like to thank you, Oded and Francesco, for your openness and for giving me the opportunity to do so. Also, I want to say thank you to Regula Oertle, the secretary of D-BAUG at ETH Zurich who made a lot of effort for helping me with the organisation of the formalities.

I would also like to thank Jorik Grolle for making available the data resulting from his master thesis. This data was crucial, without them this thesis could not have been conducted this way. Finally, I would like to thank all my friends I met at TU Delft. It was a big motivation to spend the days at university together, whether it be to talk about the thesis, have breaks or spend evenings and weekends together as a balance to work. To Francesco Bruno, who just completed his thesis in a very similar field, I am especially grateful for inspiring my work, his support in code writing and the interesting discussions together.

Sandro Tanner
Delft, January 2023

Abstract

Long-distance travels cause a large share of total greenhouse gas emissions. Environmental policy instruments aim to direct people's travel behaviour, but at present, they are not sufficiently effective. As an alternative to existing policies, there is growing attention to market-based pricing instruments. Such an innovative policy instrument is the *Tradable Mobility Credit Scheme* (TMC). It allows for the direct internalisation of externalities into the price of mobility. This study specifies a TMC which shall be internationally implemented in Europe. The objective of the study *is to estimate the impact of such a TMC on the modal split for long-distance leisure travel in Europe*. Therefore, first, a mode choice model is created to estimate the current modal split of long-distance routes in Europe. Second, the TMC is incorporated into the mode choice model, and the modal split under TMC is estimated. A case study with 73 European cities and 2,998 OD-pair connections is conducted. Flight and train ticket prices are obtained by web scraping. The credit price is found to be 193€ per ton of CO_2 under the boundary condition of reducing emissions by 30%. Hence, for a trip from Zurich to Amsterdam, a traveller bears additional costs of 31€ when travelling by plane, 5€ by train and 19€ by car. It is found that, on average, the TMC induces a decrease of the modal share of air by 12% (from 50% to 38%), an increase of the modal share of rail by 9% (from 23% to 32%) and an increase of the modal share of car by 3% (from 27% to 30%). The competitiveness of rail travel time is most critical for the modal shift towards rail. Furthermore, the TMC induces a reduction of travel demand by 17% on average for the incorporated routes. Modal shifts and trip cancellation rates largely vary between OD-pair connections.

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List of Abbreviations

CQb	“Credit Quantity willing to buy”
CQs	“Credit Quantity willing to sell”
ETS	Emission Trading System
GHG	Greenhouse Gases
OD-pair	Origin-Destination pair
Pkm	Passenger-kilometre
TMC	Tradable Mobility Credit Scheme
TTW	Tank-to-Wheel (energy chain)
VAT	Value-Added Taxes
VTT	Value of Travel Time
WTP	Willingness to Pay
WTT	Well-to-Tank (energy chain)
WTW	Well-to-Wheel (energy chain)

I. Introduction

1.1. Context

Nowadays, climate change is one of the greatest challenges that humans are facing. The effects of climate change are severe – air and ocean warming, sea level rise, more frequent and intense extreme weather events and loss of wildlife species, to name just a few. In research, there is broad consensus that climate change is anthropogenic, caused by activities that emit greenhouse gases (GHG). One of the primarily responsible activities is transport. In the European Union, the transport sector caused 29% of total GHG emissions in 2019, of which 70% is held by passenger transport (European Environment Agency, 2021).

With the Paris Agreement, a legally binding goal to limit global warming to 2 degrees Celsius was set. To achieve this goal, GHG emissions must be drastically reduced in the next decades. The transport sector has to contribute to this goal. In the last years, a reduction of GHG emissions per passenger-kilometre has been achieved through technological progress enhancing fuel efficiency. However, massively growing demand has more than eliminated the reductions. The emissions from transport have even increased with a continuous growth between 1990 and 2018 – in contrast to most other sectors which have decreased their emissions. To meet the targets, significant behavioural changes are required.

Mobility demand management is a common practice to redistribute and reduce travel demand and therefore stimulate these behaviour changes. It pursues the goal to reduce externalities which improves social welfare. Until now, several transport policy instruments to manage demand have been implemented. Common instruments for passenger transport are car ownership taxes, road tolls or flight ticket taxes. These instruments shall induce a modal shift towards more sustainable modes – modes with lower GHG emissions or lower external costs in general. However, existing policy instruments are not reducing GHG emissions to a sufficient extent to achieve the climate targets. Externalities are only partly internalised, and aviation is even exempted from some taxes**.**

Therefore, in the last years, there has been growing attention for alternative policy instruments. Such an instrument is the *Tradable Mobility Credit Scheme* (TMC). It is a market-based pricing instrument where credits are needed for travelling, for instance, based on the CO_2 emissions of the trip. Credits can be traded between travellers in a market. The price of a credit in this market adjusts to demand and supply. Supply is capped, which assures that a set emission limit is not exceeded. Until now, a TMC has not been implemented anywhere in the world. However, for the past years, research in mobility demand management has focused on TMC, since it is seen as a promising instrument. So far, the scope of TMC studies has been on a national level and mostly included land transport only. But, respecting the GHG emissions, it is crucial to incorporate long-distance travelling including air travel in the policy instrument. More than half of GHG emissions from passenger transport are caused by trips longer than 100 kilometres. Hence, there is a large potential to reduce GHG emissions in long-distance passenger transport. An internationally implemented TMC could be a solution for realising this potential and drastically reducing these emissions.

1.2. Research Objective & Research Scope

The section above highlighted that long-distance travel is responsible for a large share of total GHG emissions. A TMC is a promising instrument to reduce these emissions and therefore contribute to the achievement of the climate targets. Such an instrument would lower mobility demand, but especially shift demand towards modes with lower GHG emissions. Therefore, this thesis pursues the following objective:

Estimation of the impact of a TMC on the modal split for long-distance leisure travel in Europe

In a first step, this thesis aims to develop a mode choice model respecting the implementation of a multimodal TMC. A mode choice model which can estimate the current modal split is built. Then, a TMC is incorporated. It is presupposed to be implemented Europe-wide. The focus lies on the three modes air, rail and car. The influence of the TMC on travel behaviour and credit market behaviour is analysed and then incorporated into the model. On the one hand, the TMC will induce a change in the preferences for the chosen mode of a trip. The indicator to assess the impacts of the TMC on the modal split is the modal shift. On the other hand, the TMC will induce a change in travel demand, which will also be assessed. Furthermore, the market price of a credit is to be estimated. Derived from the modal shift and change of travel demand induced by the TMC, the mode choice model shall estimate the reduction of GHG emissions.

In a second step, a case study for European long-distance travel is conducted. The mode choice model is applied to a set of intra-European routes. This set is chosen in a way that the most relevant long-distance travel routes within Europe which are accessible by air, rail and car are covered. For the selected routes different data like travel time and travel cost are collected. These data are used as input for the mode choice model.

Figure 1 illustrates the scope of this thesis. The geographical scope comprises the European mainland plus the United Kingdom. The temporal scope consists of 2019 as the reference year (pre-covid) and 2023 as the study year. The research limits the trip purpose to leisure travel.

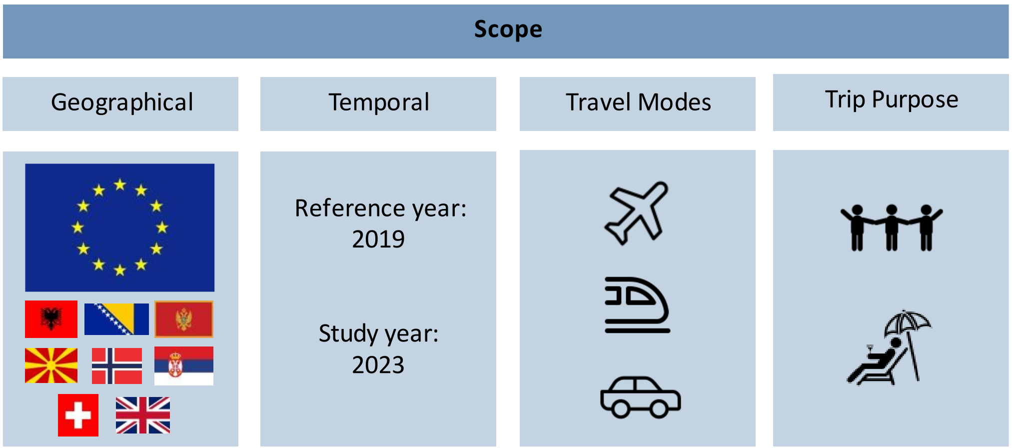


Figure 1: Scope of the research – Geographical and temporal scope, travel modes air, rail and car and trip purpose leisure

1.3. Research Questions

Directly associated with the objective is the *main research question*:

What are the impacts of a TMC on the modal split for long-distance leisure travel in Europe?

To answer the main research question, sub-questions will be answered. The first set of sub-questions provides an overview of policy instruments to reduce GHG emissions from long-distance travelling. These sub-questions will be answered through a literature review.

1. Overview of policy instruments for long-distance travel
    a. *Which policy instruments to reduce GHG emissions have been realised?*
    b. *What are the differences to a TMC?*

To later incorporate the TMC into the mode choice model, the second set of sub-questions investigate the interactions between travel behaviour and credit market behaviour. A method to determine a realistic credit price is developed.

2. Interactions between travel behaviour and credit market behaviour
    a. *How do travel behaviour and credit market behaviour interact?*
    b. *How does travel behaviour (especially mode choice) influence the credit price?*
    c. *How can a realistic credit price be estimated and what is emerging the credit price?*

The third set of sub-questions research the impacts of the TMC on travel behaviour and emissions. Thereby the main research question (see above) is answered:

3. Impacts of a TMC
    a. *What is the modal split for different European long-distance routes, without and with a TMC?*
    b. *How does demand for different modes and routes change due to the TMC?*
    c. *What is the GHG reduction for different routes caused by the modal shift and change in mobility demand, due to the TMC?*
    d. *How does the proposed TMC contribute to the GHG emission reduction target?*

1.4. Thesis Outline

In chapter *I* the context of the study, the objective and research scope as well as the research questions have been described. Chapter *II* reviews the most relevant literature about long-distance travel, its impact on GHG emissions, policy instruments to reduce these emissions and TMC as an alternative instrument. Chapter *III* describes the methodology of the research. Chapter *IV p*resents a case study applying the mode choice model. In Chapter V, the results are presented and discussed. Finally, in Chapter VI, the study is concluded by answering the research questions, discussing limitations and opportunities for further research, and providing recommendations for practice. For citation, Zotero is used, with the citation style *Transport Policy*.

Next to this report, the files listed in Appendix D have been made available under 4TU (https://data.4tu.nl/portal/).

II. Literature Review

The following chapter presents a review of the relevant literature. It starts by providing an overview of climate politics and associated GHG emission targets, followed by the contribution of transport to GHG emissions. Then, the review dives into different aspects of long-distance travel and its relation to GHG emissions. Next, a review of conventional transport policy instruments to reduce GHG emissions is provided. This is followed by an insight into research about TMCs as a promising alternative to existing instruments. Finally, a conclusion of the literature review is provided.

2.1. Paris Agreement and Green Deal

Globally, the impacts of climate change induce a growing effort to reduce GHG emissions. The legal basis to keep climate change within a limit has been set with the Paris Agreement. The therein determined goal is to limit global warming to well below 2 and preferably to 1.5 degrees Celsius. The agreement was adopted by the 21st Conference of the Parties (COP 21) in 2015 and entered into force in 2016 (United Nations, 2022). The agreement is legally binding. To meet the Paris agreement, the European Union established the European Green Deal, which is based on three objectives: no net emissions of GHG by 2050, economic growth decoupled from resource use and no person and no place left behind (European Commission, 2022). To achieve net zero GHG emissions by 2050, the European Commission created the "2030 Climate target plan". The plan contains a GHG emission reduction target of 55% for 2030 compared to the 1990 level. Figure 2 illustrates the projected GHG emissions by sector as well as removals which are needed to achieve the target. By decoupling economic growth from emissions, the GDP can keep growing.

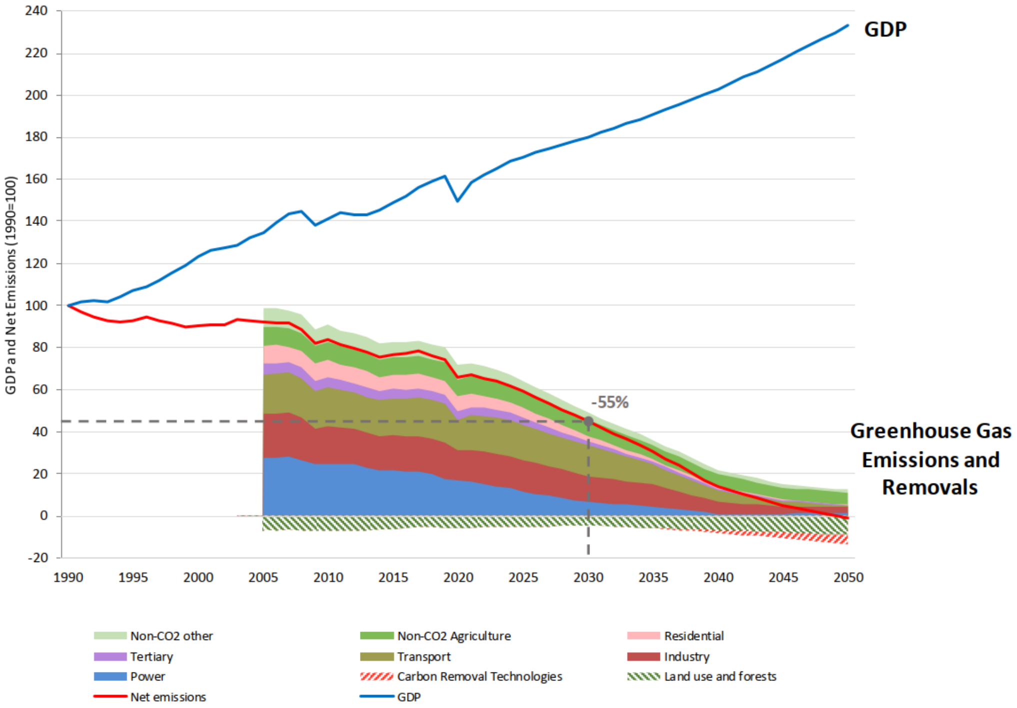


Figure 2: EU Roadmap for GHG emission reductions and decoupling from economic growth (European Commission, 2020)

2.2. GHG Emissions from Transport

While the origins of GHG emissions are manifold, the transport sector claims a large share of GHG emissions for itself. The shares of GHG emissions by sector are illustrated in Figure 3 (transport subsectors in reddish colours). It shows that transport accounts for the highest GHG emissions besides the industry sector and the energy supply sector. In the European Union, the transport sector caused 29% of total GHG emissions in 2019 (calculations based on data from (European Environment Agency, 2021)).

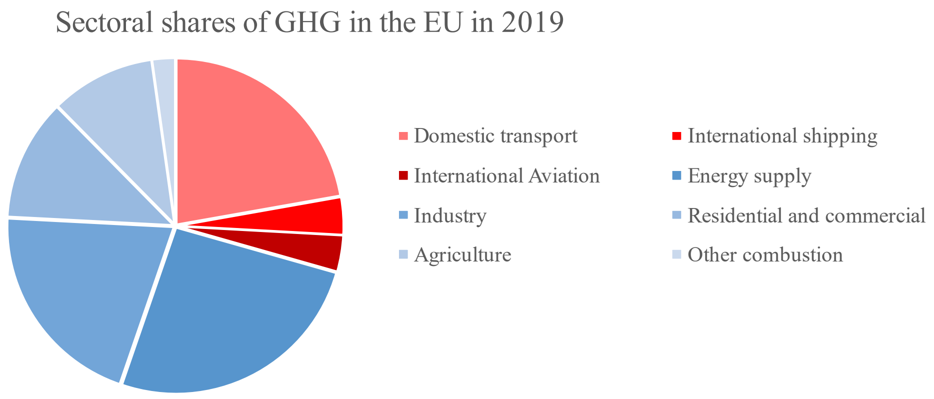


Figure 3: Sectoral shares of GHG emissions (CO_2 equivalent) in the European Union in 2019, based on data from (European Environment Agency, 2021)

While all other large sectors have reduced their emissions between 1990 and 2018, emissions from transport have continuously increased. Figure 4 shows that this applies to international aviation as well as to all other transport. For international aviation, emissions have more than doubled (see Figure 4 right). For all other transport, percentual growth has been small. However, the absolute emissions already started at a high level (European Environment Agency, 2019a).

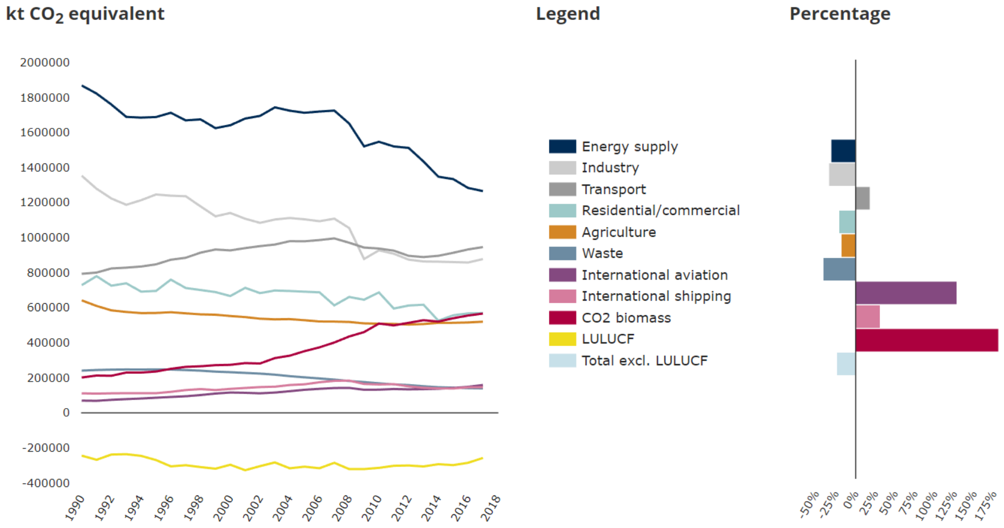


Figure 4: Evolution of GHG emissions (kt CO_2 equivalent) in the European Union between 1990 and 2017 (European Environment Agency, 2019b)

The European Commission states that all transport sectors (road, rail, aviation and waterborne transport) will have to contribute to the 55% reduction effort by 2030. By 2050, a 90% reduction in overall transport emissions compared to 1990 levels is needed to achieve climate neutrality (European Commission, 2020).

With data from European Environment Agency (2021), it can be calculated that 98.8% of all GHG emissions (CO_2 equivalent) from the transport sector in 2019 were CO_2 emissions. Therefore, in the following chapters, GHG and CO_2 emissions are not strictly distinguished and are substitutionally used depending on the literature.

2.3. Long-Distance Travel

Long-distance travel is distinguished from daily travel and is characterised by non-routine trip undertakings. The most common indicator to make a differentiation is trip distance. In the literature, an often-used lower limit for long-distance travel is 100 km. However, it remains difficult to select a delimitation. Especially if a too low distance is chosen, daily commuting trips can be higher than the distance limit and erroneously counted as long-distance trips. The distance limit is very sensitive if there are many trips close to the limit.

A broad literature review reveals that long-distance travel is not well-developed in transport research. Long-distance trips are known to be underrepresented in travel behaviour data. One important reason for this identified in the literature is the following:

> *“Most research on travel behaviour focuses on regional and local problems, like road congestion and local air pollution. Moreover, the major principals commissioning travel research are regional and national authorities, and they are mainly interested in travel and related problems with regard to their own territories. Even the supranational EU pays little attention to long-distance travel.” (van Goeverden, 2009)*

In studies, the emissions of long-distance trips are often not considered, even though more than half of passenger-transport related climate effects come from these trips (Reichert et al., 2016). Petersen et al. (2009) found that the number of trips of more than 100 km makes up about 2.5 % of all trips in Europe but accounts for about 55 % of the passenger-kilometre. Reichert et al. (2016) investigated GHG emissions in daily and long-distance travel based on national transport survey data from Germany. Trips longer than 100 km are counted as long-distance trips. They found that in the case of Germany, car travel causes by far the highest CO_2 emissions for daily travel, while for long-distance travel aviation is responsible for 67% of CO_2 emissions (see Figure 5). Car travel holds a share of 25%, public transport (rail and bus) holds a share of 4%. From a policy perspective, greater attention should be paid to long-distance trips than has been the case to this date (Reichert et al., 2016).

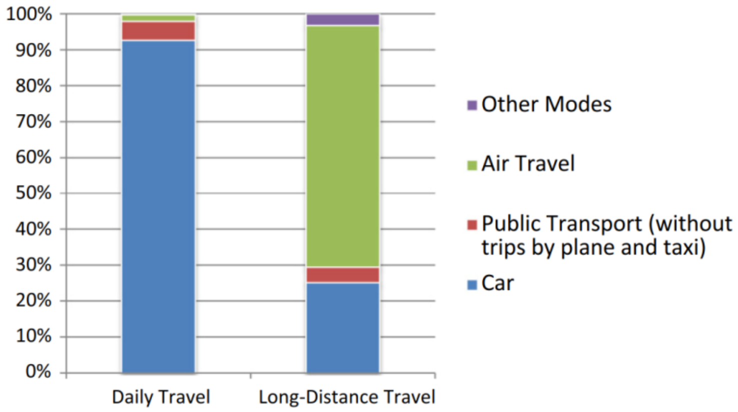


Figure 5: CO_2 emissions by transport mode in daily travel and long-distance travel (Reichert et al., 2016).

Christensen (2016) analysed the CO_2 emissions resulting from long-distance travel by residents from Denmark. She found that international travel represents 31% of the Danes' CO_2 emissions from passenger travel. Air travel is responsible for 88% of that. This is a higher share of air travel than found in Germany by (Reichert et al., 2016). This can be explained by that the latter focused on trips longer than 100 km, while the first focused on international trips, and in Germany there is a large number of national trips of more than 100 km for which mainly the car might be used.

The main travel modes for long-distance travel in Europe are the airplane, train, car and bus. Donners (2016) estimated the modal split depending on the distance travelled (see Figure 6, light-coloured lines are of relevance). The reference scenario with data from 2015 (circle symbols) shows that the share for road transport strongly decreases with increasing distance. While the share for bus is already under 10% for trips longer than 100 km, the share for car decreases slower, from almost 40% at 200 km (e.g. Amsterdam-Cologne or Zurich-Munich) to 15% at 500 km (e.g. Amsterdam – Stuttgart or Zurich-Paris). Train has the highest modal share at distances of 300 to 400 km (e.g. Amsterdam-Hamburg or Zurich-Venice). For further distances, its attractiveness decreases slowly but steadily. As must be expected, the share of air travel increases with distance. The increase is approximately linear. From distances of 500 km, air travel holds a higher share than rail travel.

These insights differ from those of Christensen (2016): She found that car as well as (but less) public transport are dominating international travel at distances less than 500 km. Between 500 and 1.000 km, there is strong competition between car, airplane and other public transport. Up to 2000 km, car is still competing with air travel. These differences from Donners (2016) could be caused by country-specific characteristics of Denmark.

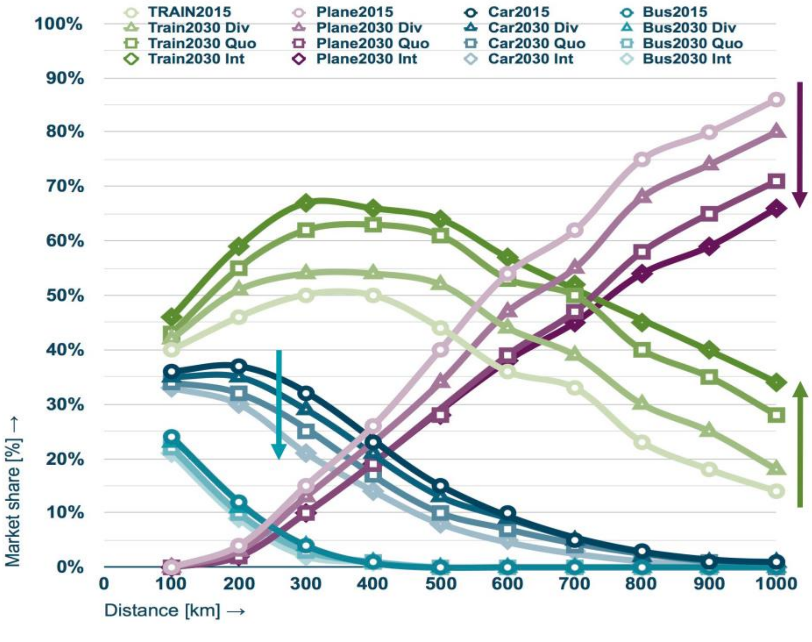


Figure 6: Modal split in different scenarios. 2015 represents the reference scenario (Donners, 2016)

2.3.1. Mode Choice Models

Under the TRANSTOOLS project, Rich and Lindhard (2012) developed the first tour-based long-distance travel demand model for passenger trips in Europe. For five modes and three different trip purposes, the model provides parameter estimates and trip elasticities for trips longer than 100 km. Rich and Lindhard (2012) identified that approximately 50% of all passenger-kilometre belong to trips longer than 100 km. This coincides with the 55% found by Petersen et al. (2009). Rich and Lindhard (2012) conclude 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”.

Mode choice models commonly incorporate utility functions consisting of variables. These variables can be distinguished between alternative-specific variables and individual-specific variables. The first are related to the service level of the transport system and also called “quality variables”, the latter are related to the traveller, household or the journey and also called “background variables” (van Goeverden, 2009). Van Goeverden (2009) emphasises that studies on the influence of variables on train choice in long-distance travel are rare. As most significant background variables have been found car ownership, number of destinations in a journey, luggage volume, gender and distance. Heufke Kantelaar et al. (2022), who investigated the willingness to use night trains for long-distance travel in Europe, state that travel purpose has a strong influence on the mode choice between plane, day train and night train. This insight coincides with other studies analysing the competition between high-speed rail and air (Heufke Kantelaar et al., 2022). Van Goeverden (2009) emphasises that most studies have focused on the influence of quality variables. Several studies found travel time to the by far the most important quality variable, and travel cost the second most important. These studies found that the number of interchanges, the obligation for seat reservation and comfort might also have a significant influence. This coincides with Heufke Kantelaar et al. (2022), who also found comfort as an important factor. Van Goeverden (2009) furthermore states that frequency is of minor importance, because on the one hand long-distance travels are more often planned in advance which makes high frequencies less important, and on the other hand waiting time related to a certain interval time between services is a relatively small part of total travel time.

2.3.2. Leisure Travel

Trips can be classified into different travel purposes, typically leisure (private), business and commute trips. Since this study focuses on leisure travel (for an explanation see section 3.6), an insight into this trip purpose is provided in the following.

Leisure is “a category of experiences with recreational and creative sub-categories, pursued with a relative sense of freedom from obligations and regarded as personally pleasurable”. Therewith leisure trips are very different from business and commute trips which are normally regarded as obligatory, not optional. In contrast to business and commute travellers who need to travel to particular places, leisure travellers can to a certain extent choose where and if they will go. Hence, leisure travellers are more flexible, more likely to change travel behaviour and more sensitive to changes in ticket prices (Leiper et al., 2008).

However, Reichert et al. (2016) identified that for leisure travel there are “strong barriers to changes in behaviour”. A reason for this is that “holidays are considered an important good warranted by a certain psychological reliance to ensure quality of life”.

In Europe, leisure trips hold by far the largest share of all long-distance trips. In the last few years, this share has been growing. The Covid pandemic has increased this trend. In 2019, leisure spending accounted for 81% and business spending for 19% of the travel and tourism spending in Europe. In 2021, the share of leisure spending increased to 84% (statista, 2022). While leisure travellers are expected to fully come back (resp. already did, depending on the world region), part of business travellers are expected to continue working and meeting remotely and are therefore expected to travel less compared to leisure travellers in the following years. On the one hand, these European spending shares coincide with the number of total trips in France. Private purposes account for 80% and business purposes for 20% of all long-distance car trips in France (Aparicio, 2016). On the other hand, they coincide with emissions from air travel in Sweden. Business travel accounts for approximately 20% of emissions from Swedish residents’ air travel (Åkerman et al., 2021).

2.3.3. Timing of Booking

The number of days between booking and departure strongly influences flight and train ticket prices. The ticket prices are highly dynamic. Usually, prices strongly increase shortly before the trip. But also, last-minute bargains often happen. Wen and Chen (2017) investigated the passenger timing of booking for low-cost airlines. They focused on leisure travel with the trip purposes *visiting relatives/friends* and *others*, whereby *others* mainly represent tourism. Figure 7 shows the cumulative density of booking time before departure by trip purpose. It can be seen that people usually start booking flights four months in advance. Between then and the day of departure the booking probability is quite constant. For the purpose *visiting relatives and friends* bookings are rather earlier than for *other*.

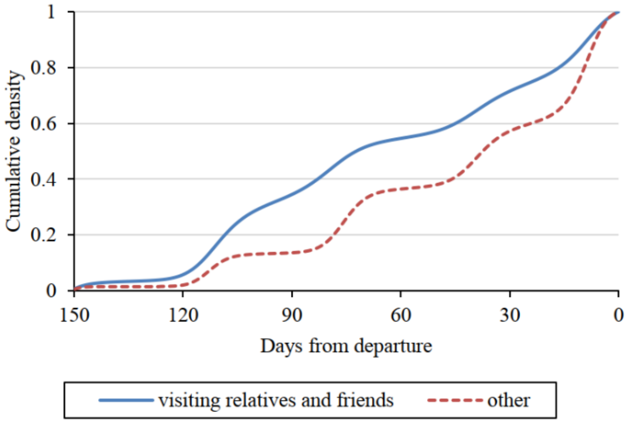


Figure 7: Cumulative density of booking time before departure by trip purpose (Wen and Chen, 2017)

2.3.4. The Role of Income

Personal income has a strong influence on someone's long-distance travel behaviour and the intensity of emissions for such trips. Reichert et al. (2016) state that income is positively associated with the distances and the frequency of private and business trips. Furthermore, high income is associated with using modes that are more detrimental to the environment, namely car and airplane. According to Christensen (2016), several analyses show that income is even the most important driver for long-distance travel. Figure 8 illustrates the correlation between the frequency of undertaking international holiday trips and the GDP per capita for a set of European countries. It is identifiable that the correlation is even higher for air travel than for overall travel (Christensen, 2016).

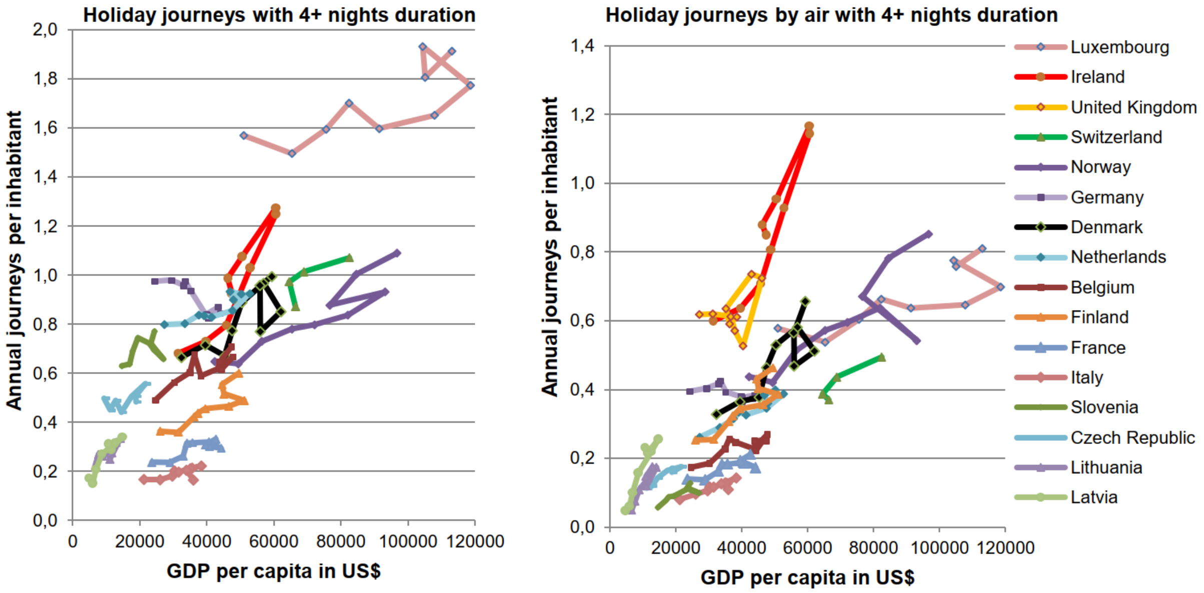


Figure 8: Number of international holiday journeys per inhabitant per year by all modes (left) and by air (right).

2.3.5. CO_2 Emissions from Air, Rail and Car Travel

As concluded before, long-distance travelling is a large source of CO_2 emissions. This section provides insight into CO_2 emissions per passenger-kilometre for air, rail and car. In the next section (*2.3.6)* the role of aviation regarding global CO_2 emissions is further elaborated on.

CO_2 emissions per passenger-kilometre depend on the mode of travel. For air and rail, values which can be found in the literature are broken down to emissions per passenger-kilometre. For car, values are indicated per vehicle kilometre. Hence, the car occupancy rate influences the emissions per passenger-kilometre – the more people in a car the lower the emissions per person. The car occupancy rate depends on several variables of which trip purpose is the most significant. In Switzerland, the average number of persons per car was 1.56 on average and 1.90 for leisure trips in 2015 (BFS and ARE, 2017). This coincides well with values from Germany, where the occupation rate was 1.5 on average and 1.9 for leisure trips in 2008 (Bundesministerium für Digitales und Verkehr (BMDV), 2010). These car occupancy rates for leisure trips match with Reichert et al. (2016) who specify a rate of 1.89 for holiday travel. The discrepancy between the average rate and the rate for leisure trips can be explained by the fact that leisure travellers commonly travel in groups while business and commuting travellers commonly drive alone.

Since there are not only emissions from the travel itself, the whole energy chain needs to be considered. There are three different scopes: Well-to-Tank (WTT), Tank-to-Wheel (TTW), and Well-to-Wheel (WTW). Well-to-Tank includes the emissions from the production of the energy source to fuel supply, Tank-to-Wheel emissions consider emissions from the movement of the vehicle, and Well-to Wheel includes both of these (Volkswagen, 2022). Table 1 provides an overview of the CO_2 emissions per passenger-kilometre for these three scopes for air, rail and car. Air travel of distances below 700 km is differentiated from air travel of distances longer than 700 km, since take-off and climbing phases, which require much more fuel than the cruise phase, have a higher weight if the travel distance is short. For car travel, the emissions per vehicle kilometre as well as per passenger-kilometre are depicted, assuming an occupancy rate of 1.9.

Table 1: CO_2 emissions per passenger-kilometre (pkm) for air, rail and car travel, considering different scopes of the energy chain (Milieu Centraal et al., 2015)

Travel mode	Well-to-Tank [kg CO_2 per pkm]	Tank-to-Wheel [kg CO2 per pkm]	Well-to-Wheel [kg CO_2 per pkm]
Air Travel Regional (< 700km)	0.019	0.278	0.297
Air Travel European (700-2500km)	0.013	0.187	0.200
Rail Travel (Intercity)	0.031	0.000	0.031
Rail Travel (High-speed train)	0.026	0.000	0.026
Car travel per vehicle (weight class and fuel type unknown)	0.039	0.181	0.220
Car Travel per person (car occupancy 1.9 persons, weight class and fuel type unknown)	0.021	0.095	0.116

The value for rail travel (High-speed train) of 0.026 kg CO_2 per passenger-kilometre (Milieu Centraal et al., 2015) coincides with the value from Bleijenberg (2020) who estimates a European average of 0.025. From Table 1 it can be derived that air travel causes 6.5 to 11.4 times more CO_2 emissions than rail travel (WTW scope). Travelling by car causes 3.7 to 4.5 times fewer emissions than air travel, assuming a car occupancy of 1.9. However, for further distances, travelling by car as a single person can result in more emissions than flying.

2.3.6. Further Review on CO_2 Emissions from Aviation

Globally, aviation causes 2.4% of total CO_2 emissions (Bleijenberg, 2020). As stated before, air travel is responsible for a large share of emissions from long-distance travel in Europe. In the European transport sector, with an increase of 129% international aviation caused the largest percentual raise of GHG emissions over 1990 levels (European Environment Agency, 2019c). Regardless, the aviation sector will be required to contribute to the 90% reduction target of the European Green Deal (Ricardo, 2021).

Christensen (2016) found that CO_2 emissions from air travel are 1.1 tonnes per capita per year in Denmark. 47% of these emissions are produced inside European mainland destinations or hubs (including Great Britain and Ireland). Christensen (2016) furthermore emphasises that air travel is the fastest-growing passenger mobility segment in both the number of journeys and travel distances, with an annual increase of 5.5% over a 10-year period.

The location of emitting CO_2 affects the impact on the climate. CO_2 emission at a height of 10 km is assessed to burden the climate twice as much as the same CO_2 emissions at ground level (Christensen, 2016). Consequently, a ton of CO_2 emitted from an airplane while cruising has a stronger impact on the climate than a ton of CO_2 from land transport. (Åkerman et al., 2021) state that the total warming effect of aviation is uncertain but estimated to be 1.7 times as high as that of CO_2 alone, measured as GWP100 (Global Warming Potential with a 100-year horizon). The reason lies in the emissions of water vapour which can cause contrails and cirrus clouds under certain atmospheric conditions.

Bleijenberg (2020) suggests different options to drastically lower the contribution of aviation to climate change: technical improvements in aircrafts and engines, improvements in air traffic management and infrastructure use, development and deployment of (hybrid) electric aircrafts, use of advanced biokerosene, reduced growth in air travel through a shift toward train trips, reduced growth in air travel through internalisation of external costs and reduced growth in long-distance travel in general.

2.3.7. Modal Shift towards Rail

Long-distance travel will struggle to achieve the climate targets:

> *"Even with slow economic development and an advanced application of transport policy, European long-distance travel would be far from meeting the previous 2050 EU-target of −60% compared to 1990. With the newly updated stronger EU climate policy, targets would be even more difficult to reach. The IEA (International Energy Agency) estimates that emissions from aviation could be reduced by 60% to 2030, but that this would require significant behavioural changes. (Åkerman et al., 2021)*

Åkerman et al. (2021), who identified possible long-distance travel futures that are in line with the Paris agreement, emphasise that significant behavioural changes are needed. Such a behavioural change is the modal shift from air and car towards rail. From an environmental perspective, rail travel is much better off than air and car travel. Such a modal shift is seen as the "main potential for reducing GHG emissions" (Åkerman et al., 2021). In the last years, there have been conducted several studies about how this shift can be achieved for long-distance travelling in Europe.

Generally, mode shift towards rail can be accomplished either by improvements of the level of rail service (pull towards rail), mainly to shorten travel time, or by mobility demand management (pull towards rail and/or push away from air and car). Pagliara et al. (2012) investigated the competition between high-speed rail and air transportation for the corridor between Madrid and Barcelona. They found that to make high-speed rail more competitive with air travel, several aspects must be worked on – mainly on the reduction of travel time, but also on frequency and price. This only partly coincides with the insights from section 2.3.1, where the price but not frequency was found to be significant.

However, studies have also pointed out barriers which hinder the shift of long-distance passengers to rail. One important barrier to not changing to sustainable travel modes is the lack of their availability or their insufficient level of service (Arnadottir et al., 2021). Pagliara et al. (2012) emphasise that increasing frequency and lowering prices is from an economic view only possible if demand is high enough. Consequently, if this is not the case rail is hardly able to compete with rail.

The potential CO_2 reduction if these barriers can be overcome is large. Bleijenberg (2020) estimated the CO_2 reduction of shifting intra-European aviation to rail, assuming different improvements in the level of rail service (high-speed rail between all larger cities in Europe, all railway services 10% faster and a 50% increase in night train supply). He found a potential reduction of 4 to 7 Mt CO_2, which corresponds to 6% to 11% of the CO_2 emissions from intra-European aviation. Bleijenberg (2020) emphasises that in addition to rail service improvements, policies which discourage flying are required.

To achieve a mode shift, social acceptance is required. Under a European public opinion poll with over 6.300 adults, (Europe on Rail and Germanwatch, 2021) the willingness to travel by rail instead of by plane was analysed. It was found that 37% of the people are willing to spend more than 5 hours on a train for a trip that could have been undertaken by plane. For more than 7 hours it is 23% of the people and for the rest of the people, it is less than 5 hours. The study also found that 62% of the respondents are interested in taking trains for European travel. Furthermore, 73% of the people say that travelling by rail should be cheaper than flying and 52% say that they would support a carbon tax.

2.3.8. Value of Travel Time

As mentioned before, a main reason why shifting demand from air to rail is limited is the often much higher travel time for rail for distances longer than about 500 km. Here, the value of travel time (VTT) plays a role. The lower the VTT, the more competitive rail can be for large distances. There is a wide variety of research about VTT. The value can differ a lot depending on factors like country context, GDP (income), trip purpose, the component of the trip (e.g. in-vehicle, waiting, access, egress), distance and comfort level. Wardman et al. (2016) conducted the so far most extensive meta-analysis of VTT. It includes over 3.000 valuations from 26 European countries. The average VTT is 12.43 € per hour for commuting, 29.59 for business and 11.82 for other trips. For all trip purposes, the average is 17.86. Mabit et al. (2013) who investigated international long-distance travel at the Fehmarn Belt (Baltic Sea) found on the one hand, that the VTT decreases with distance and duration, on the other hand, that VTT is higher for air travel.

Hu et al. (2022) looked at VTT from a macroscopic view. They relate it to GDP, population and working hours. The value can be calculated by dividing the GDP by the population and the average working hours of workers in a certain area. This is comprehensible because it equals the average value of the goods and services produced by one person in one hour in this area. Therefore, it expresses the loss resulting from travelling for an hour instead of working for an hour.

Malichova et al. (2022) looked at VTT from another perspective and researched *worthwhile travel time* and the perceived value of travel activities in long-distance trips in Europe. In the concept of *worthwhile travel time*, travel time is considered either worthwhile or wasted. It is worthwhile if time can be used for personal productivity, work-related productivity, or enjoyment. Malichova et al. (2022) found that long-distance car or plane travellers are less likely to evaluate trips as worthwhile than train or bus travellers. The reason for this is that “the train appears to offer the most potential for a high quality and therefore attractive experience as an alternative to the car” since there is a “wider range of valuable onboard activities other than caring for the trip itself”. Focusing more on the *worthwhile travel time* could decrease the VTT when travelling by train and therefore strengthen the shift towards rail.

2.4. Conventional Policy Instruments to reduce GHG Emissions

The section before has explored the characteristics of long-distance travel, its contribution to GHG emissions and the necessity to reduce its GHG emissions. The European Commission emphasises that a combination of different solutions is needed so that the transport sector can contribute its part to the climate target:

> *“A smart combination of vehicle/vessels/aircraft efficiency improvements, fuel mix changes, greater use of sustainable transport modes and multi-modal solutions, digitalisation for smart traffic and mobility management, road pricing and other incentives can reduce greenhouse gas emissions and at the same time significantly address noise pollution and improve air quality.” (European Commission, 2020)*

Strategies to reduce GHG emissions can be differentiated between enhancing efficiency (e.g. technological development, more effective resource usage) and reducing consumption. The latter happens on two tiers. On the first tier, people are becoming more aware of the impacts of their behaviour on greenhouse gas emissions, which leads to a voluntary change of behaviour towards less greenhouse gas emissions. On the second tier, which is required because voluntary behaviour changes are often not sufficient, consumption is steered by policy makers, known as *Demand Management*. Here behaviour towards less GHG emissions is stimulated by implementing environment policies. Such policies often follow the idea of imposing taxes in order to internalise external costs (known as *Pigouvian Tax)*. In the following, an overview of policy instruments to reduce external costs, especially GHG emissions from road transport and aviation is presented. Due to the scope of this study, the focus lies on Europe.

2.4.1. Road transport

The main instrument to internalise external costs from road transport is taxation. Transport taxation can function as demand management as well as to finance public spending. Schroten and ‘t Hoen (2016) distinguish between vehicle taxes, tolls and vignettes, fuel excise duties and value-added taxes (VAT).

Vehicle taxes, levied per vehicle, are usual all over the EU. Most countries levy a periodic ownership tax on vehicles. Some countries also charge a fee on vehicles entering the fleet (registration tax). These taxes are often based on engine size, engine power and CO_2 emissions. Tolls and vignettes are an instrument to charge for using the infrastructure, applied in most EU countries. It can be differentiated between distance-based systems (tolls) and time-based systems (vignettes). The price level is commonly based on vehicle type. Fuel excise duties are applied in all EU countries. The levy depends on the type of fuel and varies by country. In 2013, it ranged from about 300 (Diesel in Eastern-European countries) to 750 € per 1.000 litre (Petrol in the Netherlands). Value-added taxes are levied on the purchase of vehicles and fuel. They also depend on the country-context and varied from around 15% to 27% in 2013 (Schroten and ’t Hoen, 2016).

2.4.2. Aviation

For aviation, there are different types of policy instruments pursuing the goal of reducing GHG emissions. The policies can be classified into taxation, emission trading and carbon offsetting. The most implemented policy is taxation. Taxes can either be levied from airlines on seats, flights, and aviation fuel or from passengers on flight tickets. The most common tax is the flight ticket tax which has been introduced by many countries. Most of them have two or three single fees which are added to the ticket price: One for short-haul flights, one for long-haul flights and possibly one for medium-haul flights (Krenek and Schratzenstaller, 2017). Figure 9 shows the average taxation (sum of all taxes) in the EU and EFTA. There are large differences in taxation: While taxation in the United Kingdom is around 40€, some countries do not levy taxes at all.

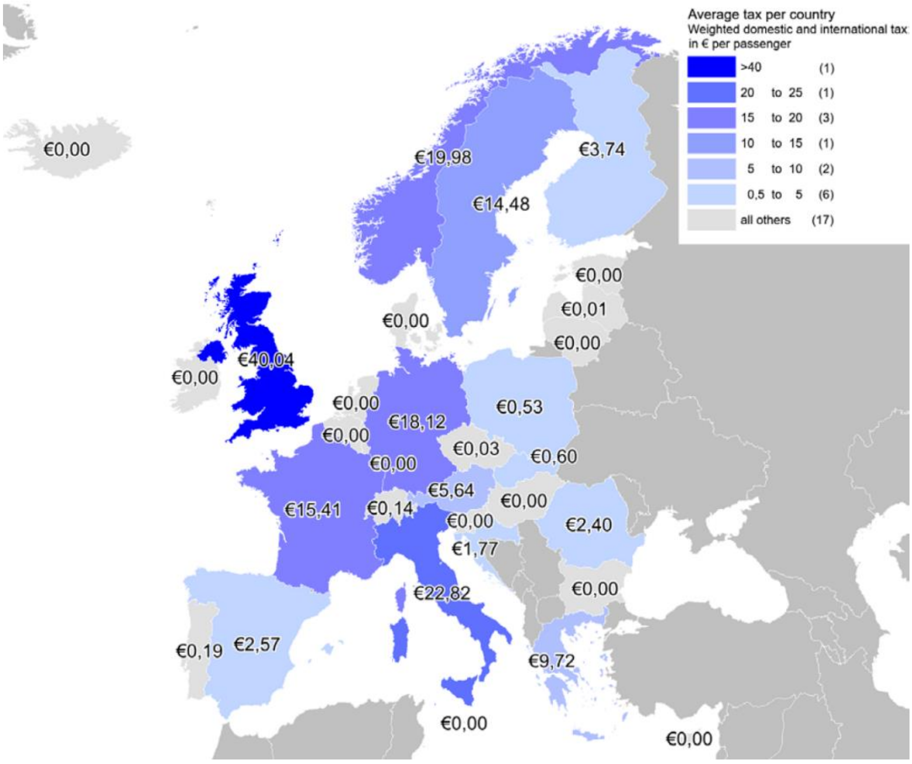


Figure 9: Average aviation taxes per passenger in the EU and EFTA. Weighted average for domestic and international passengers (CE Delft and European Commission, 2019)

This existing taxation system has two strong limitations regarding environmental effectiveness. First, due to its blunt characteristics, it does not consider the actual emissions caused by air travel. Second, the national implementations induce tax competition, which can be perceived as unfair and leads to a general under-taxation. Also, capacity can potentially be moved to other markets (Denstadli and Veisten, 2020). This can lead to a situation that the expected CO_2 reductions are not achieved because, for example, people might choose an airport in a neighbouring country which has lower taxation.

In addition to these limitations, tax privileges caused by several international rules and agreements lead to a low share of internalised costs of CO_2 emissions, compared to other economic activities. The first tax privilege is that for international flights, value-added-tax is zero for airlines' inputs like the acquisition of aircraft and fuel as well as for airlines' outputs like tickets sold. The second tax privilege is that fuel used for international flights is exempted from the mineral oil tax (Krenek and Schratzenstaller, 2017).

Krenek and Schratzenstaller (2017) propose to introduce carbon-based specific taxes at the European level. Such taxes have not been implemented at all. The idea behind this is that the actual environmental impact of a passenger on a specific flight is taken into account. It requires the assignment of a price to the emissions associated with a flight. The costs for the taxes are paid by the airline and therefore partly passed on to the traveller. Carbon-based specific taxes would be environmentally effective because they would provide incentives for airlines to reduce their fuel use. Denstadli and Veisten (2020), who explored Norwegian air travellers' willingness to pay (WTP) for carbon taxes, state that a large share of passengers would accept a carbon tax if it was mandatory for all travellers. They emphasise that travellers have a higher willingness to pay for emission costs than that already included in their ticket price. These findings are supported by Sonnenschein and Smedby (2019) who conclude that a mandatory ticket tax is a "viable policy option that might receive majority support among the population".

An alternative to taxation is the EU emission trading system (ETS). It is a cap-and-trade system which contributes to the internalisation of CO_2 emissions. The cap defines limits for carbon emissions from intra-European flights. 82% of the emission rights are allocated for free of charge to airlines, as grandfathering, and therefore are not beneficial for the climate. Only 15% of the emission rights are auctioned, and the remaining are set aside for new entries. The maximum emissions of intra-European aviation are not controlled with ETS, since airlines can purchase EU Allowances for all emissions exceeding the cap. Additionally, the price of these EU Allowances is too low to fully internalise the CO_2 emission costs. Since the limit of emissions can be exceeded and it includes only intra-European flights, the impacts of ETS remains low (van Geuns, 2021).

Another climate policy is carbon offsetting, where emissions are compensated through carbon reductions in another location, for instance by an afforestation project. On the one hand, offsetting happens on the airline level. The carbon offsetting scheme CORSIA is the first global air travel emission mitigation policy. Emissions which exceed the level of 2019 have to be compensated. Hence only costs of emission growth are internalised (van Geuns, 2021). On the other hand, passengers can offset their emissions under voluntary carbon-offsetting programs. However, Denstadli and Veisten (2020) emphasise that only 2 to 10% of travellers participate. A higher share of travellers is willing to participate, but only if fellow passengers also do it, to "share the burden".

Fleming and Chamberlin (2011) generally criticise the existing climate policies. They state that these policies have their limitations because of the nature of how they work.

> *“Climate policy is not, at present, reducing carbon emissions on a scale which has any relevance to the real task of maintaining a stable climate. There are many reasons for this. One is that policy is conceived as a top-down process, allowing little or no participation by energy users outside the small circle of professional debate and expertise. The citizen is on the receiving end of instructions about energy use, but has no active part to playing, thinking about it. He or she is not invited to develop means of achieving the deep reductions that are required, radically changing lifestyles and fossil fuel dependency, and working with local communities in achieving this.” (Fleming and Chamberlin, 2011)*

The next chapter introduces Tradable Mobility Credits, an alternative policy instrument. As a market-based instrument, it could have the potential to overcome these mentioned limitations.

2.5. An Alternative: Tradable Mobility Credits

As an alternative to taxes for reducing the CO_2 emissions of transport, there is growing attention to market-based pricing instruments. These cap-and-trade instruments are economically attractive as they can reach a certain reduction goal at minimised aggregate costs. The instruments are able to eliminate externalities:

> *“The lack of well-defined property rights causes the existence of externalities. These externalities could be eliminated if resource users could trade delineated private access rights in a market, which would lead to the efficient use of the resource” (Dogterom et al., 2018)*

Such a market-based instrument is the *Tradable Mobility Credit Scheme* (TMC). In this scheme, credits are needed to access the transportation network. Until now, a TMC has not been implemented anywhere in the world. However, for the past years, research in mobility demand management has been focused on further developing this instrument. The ongoing DIT4TraM project funded under the European Union’s Horizon 2020 delivers state of the art and concepts of TMCs (Balzer et al., 2021).

2.5.1. Concept of TMCs

Under a TMC, the credits are indifferent, like currency units (Balzer et al., 2021). The number of credits needed to access the transportation network depends on what wants to be internalised with the TMC. Often, this is the CO_2 emission of the trip. Besides emissions, Balzer et al. (2021) also propose the chosen route, departure time and transportation mode as criteria for the determination of the number of credits needed for a trip.

Balzer et al. (2021) foresee that TMC replace existing taxes like road pricing and motor vehicle tax. At the beginning of a defined time period, credits are distributed to citizens by a governmental institution. Balzer et al. (2021) propose either an equal distribution or taking into consideration the traveller’s heterogeneity, by for example allocating more credits to low-income people who are dependent on a car. If a person’s credit expenditure exceeds the institution's allocated credits, the person must purchase additional credits. Citizens with a lower expenditure can sell their remaining credits to the people who need additional credits. This trade happens in a centralised market. The price of the credit is dynamic. It adjusts to demand and supply. Supply is the number of totally allocated credits, based on the emissions reduction target set by the politics. Hence, total emissions are capped and cannot be exceeded. Assuming that credits represent CO_2 emissions, demand corresponds to the sum of all individual CO_2 emissions from transport. Aziz et al. (2015) and Tian et al. (2019) propose a market with a double auction mechanism, which is commonly used in stock markets and markets for financial instruments. In such a market, potential buyers submit their bids and potential sellers submit their ask prices. This generates a price which clears the market: Sellers who asked less than it, sell at that price, and buyers who bid more than it, buy at this price (Wikipedia, 2022a).

TMC can be compared to Tradable Energy Quotas investigated by Fleming and Chamberlin (2011). They work conceptually like TMC. In contrast to TMC, they include all CO_2 emissions and not only these from transport. Like TMC, they have not been implemented. However, TMC can be compared to concepts which already exist and have been proven to be successful. The idea of TMC is comparable with ETS (see 2.4.2 Aviation). But while ETS works on the firm level, a TMC applies to every individual citizen. Dogterom et al. (2017) also mention fishing quotas and airport slot allocations as comparable concepts. However, they as well are only applied on a higher level and not the individual citizen level.

Balzer et al. (2021) state three main objectives of a TMC. First, it shall reduce the sum of travel times of all travellers, hence reducing delay from congestion. Second, it is meant to reduce environmental externalities, also by reducing congestion. These two objectives allow for the direct internalisation of externalities into the price of mobility. Third, it shall contribute to equity. Allocating credits for free to all citizens allows everyone to travel to a certain degree. People whose intensity of travel is below that degree can financially benefit from selling credits, which is especially advantageous for low-income people. Furthermore, allocation can be variable to address equity issues. For instance, allocation can be based on the accessibility of the place of residence. People living in the city would receive fewer credits than people living in the countryside. Latter might be dependent on the car, as public transport might not be sufficiently available, and therefore need more credits for example to be able to reach a job.

2.5.2. Comparison to Conventional Policy Instruments

The rate of taxation is defined by politics and does not change over time as long as it is not decided to do so. Under tax policy, the total extent of travelling is not capped. Under a TMC it is the opposite: The credit price is variable, and the total extent of mobility (respectively total emissions from mobility) is a constraint determined by the total credit supply.

A TMC holds several advantages compared to conventional taxes. For the following reasons, TMC could be more socially accepted than taxes. First, a TMC contributes to mobility equity. While under a TMC 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 and Chamberlin, 2011). Second, money does not flow to regulating authorities, and citizens can – if they do not use all their initially allocated credits – even financially benefit. Third, TMC can have a psychological advantage compared to taxes: by receiving credits and being able to trade them, there emerges “a sense of ownership”, with a higher degree of participation of the individuals and legitimacy (Fleming and Chamberlin, 2011). Furthermore, since the credit supply restricts the total extent of mobility respectively total emission from mobility, it is made sure that achieving the CO_2 target is always guaranteed.

2.5.3. Effectiveness of TMC

“What motivates people to carry out a difficult task – one requiring thought and inventiveness – is, above all, confidence that the task is an interesting and worthwhile one. There must be a sense that it is in their own direct interests to participate, a belief that they can rely on the cooperation of others, and an assurance that those managing the scheme are accountable to the participants, and are themselves required to participate.” (Fleming and Chamberlin, 2011)

Therewith, Fleming and Chamberlin (2011) argue why Tradable Energy Quotas must be a promising argument. Holding the same characteristics, the argument can be transferred to TMC. Raux et al. (2015) emphasise that the kind of social norm associated with a personal allowance fixed within a common target could help to activate pro-environmental behaviour. Dogterom et al. (2017) reviewed empirical research and concluded that TMC for car travelling is able to achieve changes in people’s car use. Studies have shown that the effectiveness of a TMC in the reduction of kilometres travelled is equal to or even beyond the effectiveness of other financial incentives with equivalent costs (Dogterom et al., 2017). However, Raux et al. (2015) found that although people are willing to reduce their car travel in all of the distance categories, there is a tendency to protect long and very long trips – weekend and holiday trips are the last to be changed.

For aviation, there are also strong indications for a higher effectiveness of a TMC than of existing instruments. Compared to ETS, this has the following reasons: On the one hand, under ETS airlines can purchase additional emission allowances which leads to an excess of total emissions (van Geuns, 2021). Under a TMC this is not the case. On the other hand, under ETS the costs for allowances are first paid by the airline and therefore not necessarily fully passed on to the traveller (Krenek and Schratzenstaller, 2017). Under a TMC, the costs for the internalisation of the CO_2 are fully borne by the traveller.

Aziz et al. (2015) investigated car travel behaviour under a TMC (CO_2 credits) with a real-time experimental game. They found that people with low-income are mostly selling surplus credits. However, some low-income people are not willing to sell which can lead to a scarcity of credits available in the market. They also found hoarding behaviour. People were saving credits for future use. The results furthermore showed that people are more likely to save credits on their non-work trips, especially in higher income groups. Also, for recreational trips, the elasticity values to credit costs are much higher. Tian et al. (2019) looked at behavioural effects that characterize responses to a TMC in personal car use. They observed loss aversion, which describes the propensity to prefer avoiding losses to obtaining equivalent gains. It implies that people have a higher tendency to reduce credit usage in a situation of credit shortage than in a situation of credit surplus.

Although different studies have shown that TMC has the potential to be an effective policy instrument, large research gaps are remaining. Dogterom et al. (2017) conclude that on the one hand, studies “have investigated stated behavioural change in response to TMC in a rather abstract fashion”. Therefore, there is large uncertainty about how realistic these stated behavioural changes are. Studies should focus on the context of people’s everyday activity patterns, for example by using a set of concrete activities/trips. On the other hand, they conclude that studies have largely overlooked the “option to either gain or lose money under the measure, the need to manage credits over time, and the presence of uncertainty surrounding future credit availability and credit prices.” Hence, not much is known about behavioural effects under a TMC.

2.5.4. Credit Price

A TMC holds a market where credits are traded to a certain price. This price is the equilibrium price according to demand and supply. The question of which price can be expected arises. Therefore, an insight into studies about the effective price of CO_2 and the WTP for external costs from CO_2 is provided.

OECD (2013) compared the price put on carbon by policies in different countries and sectors. The carbon price which is required to have an effective environmental policy was estimated. For road transport, they estimated effective carbon prices of 65 to 153 € per ton of CO_2 for European countries (see Figure 10). These represent the total costs of carbon to society (external costs). However, the uncertainty is large, so the price range goes up to far over 1.000 € per ton of CO_2 (Denmark and Estonia).

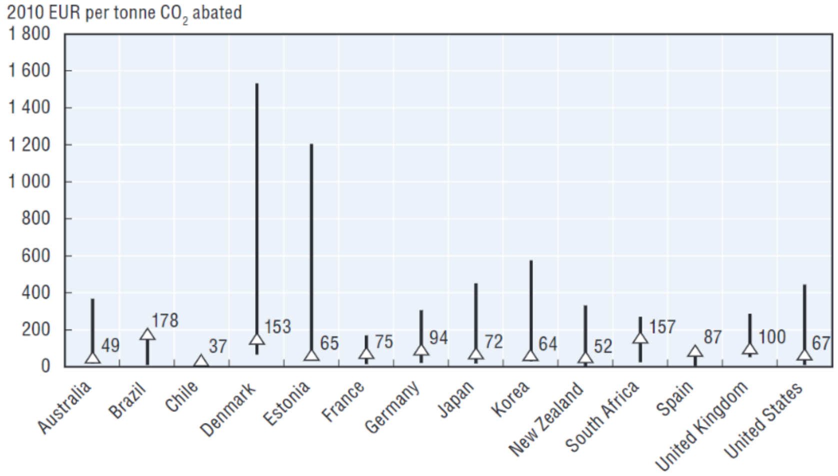


Figure 10: Transport sector carbon price, weighted average and range per country (OECD, 2013)

Alberini et al. (2018) estimated the WTP for CO_2 emissions avoided by Italian and Czech households, with help of discrete choice experiments. They found 133€ for Italian and 94€ for Czech respondents, which lies in a comparable range to the values in Figure 10. They also found that income is a strong driver for the WTP, which coincides well with the insights from section 2.3.4. Sonnenschein and Smedby (2019) investigated the WTP of Swedish people for a mandatory air ticket surcharge for climate change mitigation. They found values of 50 € per ton of CO_2 for short-distance flights and 30 € per ton of CO_2 for long-distance flights. The WTP was higher for non-frequent flyers. Åkerman et al. (2021) used another approach: They estimated the future cost of carbon capture and storage. Therewith they derived the external cost of one ton of CO_2 emission – they estimated a range between 100 and 200 €. Furthermore, Ricardo (2021) obtains a value which matches this range: According to the Energy Taxation Directive, the European Union’s framework for the taxation of energy products, a current minimum cost of 131€ per ton of CO_2 was estimated.

2.6. Conclusion

The literature review has shown that long-distance travelling is a growing mobility segment responsible for a large share of total CO_2 emissions. Shifting demand towards rail is seen as a main pillar that long-distance transport can contribute to the achievement of the climate targets. However, existing policy instruments do not sufficiently incentivise travellers to use the train instead of the plane or the car. It has been explored that market-based pricing instruments can be a great opportunity to more effectively reduce externalities from transport. Research efforts on Tradable Mobility Credits have strongly been intensified. They have not been implemented anywhere, but similar concepts in other fields are proven to be successful. Also, it has been found that there is social acceptance of such concepts at least to a certain degree. However, there are applications of TMCs that have not been investigated. On the one hand, existing studies have focused on TMCs which would be implemented nationally, and which would incorporate land transport only. So, the TMCs of these studies do not include long-distance travel. On the other hand, there is a knowledge gap about the implications of TMCs. Dogterom et al. (2017), Aziz et al. (2015) and Tian et al. (2019) pointed out that there is a lack of knowledge about the market behavioural effects of the TMC, trading patterns and uncertainty surrounding future credit availability and credit prices. Also, to the author's knowledge, existing studies do not estimate the impacts of the TMC on the modal split.

This study is an attempt to address part of these research gaps by estimating the impacts of the TMC on long-distance travel behaviour. Immersing in long-distance travel itself is a challenge and an opportunity to contribute to transport research. It has been explored that studies in transport often focused on short-distance daily travel and neglected long-distance travel. Long-distance models are scarce and some knowledge about parameters is lacking. Therefore, to build a mode choice model incorporating a TMC, numerous assumptions are required. Predominantly, they are based on findings from studies explored in this literature review.

III. Methodology

Chapter II provided an overview of long-distance travel, its interconnection with GHG emissions and existing policy instruments to reduce these emissions. A review of recent research about TMCs as a new concept to reduce emissions from transport was presented. One could conclude that in transport literature there is a lack of knowledge of long-distance transport as well as of the impacts caused by the implementation of TMCs. This study aims to provide a contribution to transport research by developing a mode choice model which can estimate the impacts of a TMC on the modal split. This chapter III describes the approach to developing this model. In Chapter IV the model will be applied to a specific European study perimeter. All scripting is conducted with PyCharm. Some maps are created in PyCharm with the Matplotlib Basemap package, other maps are created in QGIS. The structure of the python script is shown in Appendix A.

3.1. Specification of TMC

In the present section, the characteristics of the TMC are defined. They will influence the approach of including the TMC in the mode choice model. Since the mode choice model is scoped at the European continent, some of the assumptions made in this methodology are tailored to the European context.

3.1.1. Internationality

So far in the literature, the scope of TMCs has been on a national level and mostly included land transport only. To the author’s knowledge, there has not been a study about a TMC including air travel. This thesis aims to extend the scope of the implemented TMC to a multi-country level. Since aviation is responsible for a large share of transport’s CO_2 emissions, it is seen to be crucial to incorporate it in a TMC. As explored in section 2.3.6, Bleijenberg (2020) suggests different options to lower the contribution of aviation to climate change. From these options, the last three – reduced growth in air travel through a shift toward train trips, reduced growth in air travel through internalisation of external costs and reduced growth in long-distance travel in general – are all tackled by such an international TMC.

3.1.2. Management of the TMC

One central authority formed by all participating countries shall be responsible for the management of the TMC. This central authority shall be responsible for the credit supply (see 3.1.4), for the imposition of credits (re-collecting the credits people spend when they travel) and for the provision of a central credit market where people can trade credits.

3.1.3. Credit Unit

As described in section 2.5.1 credits can be seen as a currency. It is chosen that one credit corresponds to 1 ton of CO_2 emissions. For example, a flight from Amsterdam to Zurich (600km) causes 0.178 tons of CO_2, assuming the emissions indicated in Table 1 in section *2.3.5*. Hence, 0.178 credits need to be spent for undertaking this trip, The value of one credit depends on the market price, which adjusts to demand and supply and is therefore dynamic over time. It is of great importance that there is only one market price. Different prices would immediately lead to black market brokerage and the scheme could possibly break down (Fleming and Chamberlin, 2011). If the market price for one credit is for example 200€, the credit costs for the flight from Amsterdam to Zurich would be 36€, assuming that the traveller buys these credits on the central market.

3.1.4. Credit Allocation

There are different alternatives to how the central authority can allocate credits to citizens. Credits can either be allocated for free by the central authority or can be sold by the central authority for a price. If the allocation is for free, the credits can be equally distributed to all citizens or proportionally according to certain criteria which reflect the individual need for credits. Such criteria could be the GDP, the current travel intensity or current CO_2 emissions from transport. If the credits are sold by the central authority, the price can be static and defined by the central authority or it can be equal to the market price (the same price as the traded credits which adjusts to demand and supply). These options could cause poorer people cannot afford to travel long-distance anymore. Therefore, it could be thought of implementing an instrument that citizens receive subsidies, for example, according to their origin country or their salary. Table 2 provides an overview of these options with some thoughts about their advantages and disadvantages.

Table 2: Possible ways to supply credits

Option	Allocation Credit Costs	Allocation Distribution	Advantages	Disadvantages
1	Free	Equally	+ Mobility equality + Simple implementation	– Large money and credit flow between richer and poorer countries – Loss of incentive to work and finance live by credit selling in poorer countries?
2	Free	Proportional to criteria	+ Less distortion of mobility behaviour and market + Addressing equity issues	– Unfair for poorer countries? – Criteria possibly perceived as arbitrary – Long political process
3	Defined, static price	-	+ Everyone can buy a certain number of credits for a reasonable price (in case market price explodes)	– Mobility inequality
4	Same as market price	-	+ Justifiable as long-distance travel is not a basic need and already now poor people hardly travel long-distance. Simple implementation.	– Mobility inequality (very strong if market price is high)

A TMC would replace conventional taxes, which could cause difficulties. Especially countries which are much dependent on revenues from conventional taxes could face financial problems. Yet, these allocation options and their advantages and disadvantages are not further analysed. For the further methodology of this study, it is decided that credit allocation costs are free, and allocation is carried out equally to every citizen of all countries within the perimeter (option 1). As described in section 2.5, this option contributes to mobility equity. It is therefore the most socially acceptable option as everyone has to a certain extent fair access to long-distance travel.

3.2. Behaviour Elements and Dynamics

The TMC induces three behaviour elements. First, with the allocation happening at the beginning of a time period (e.g. one month or one year), citizens receive credits from the central government. Second, citizens can trade credits with each other (buy and sell for the current market price). Third, when people travel, they transfer credits back to the central authority according to the CO_2 emissions of their trip. Figure 11 graphically shows these behaviour elements in interaction with trip undertakings.

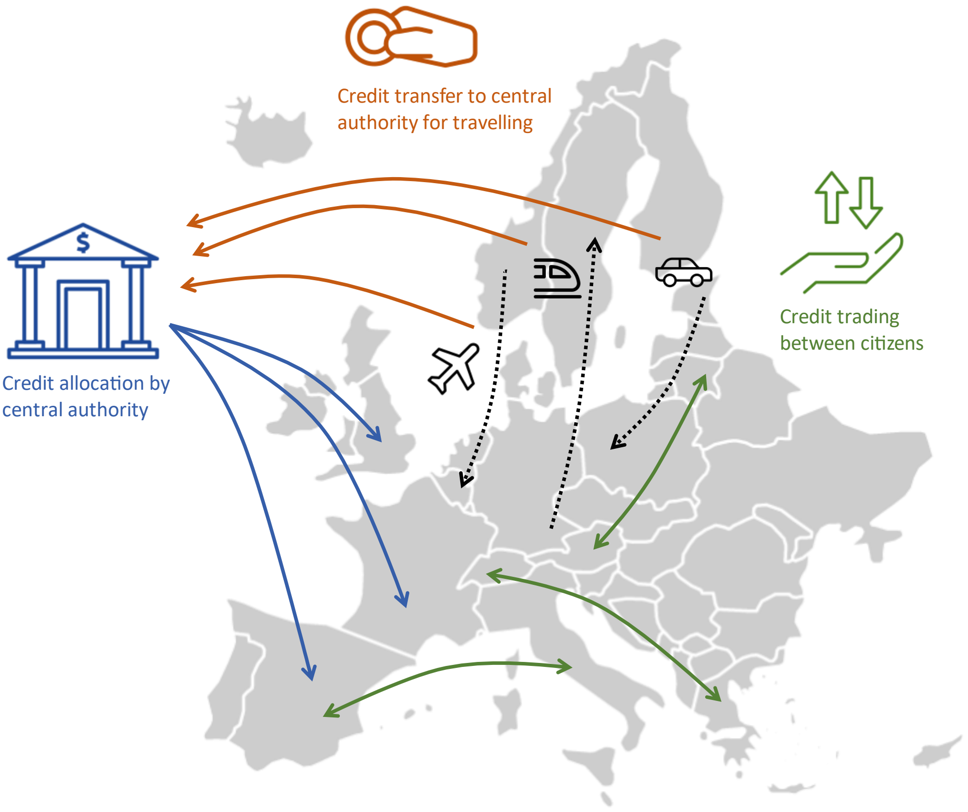


Figure 11: Behaviour elements under a TMC illustrated with the map of Europe

In the following, it is distinguished between travel behaviour and credit market behaviour. The first includes changes in the travel behaviour induced by the TMC, the latter comprises the trading of credits. To include the above proposed TMC in the mode choice model, the interactions between travel behaviour and credit market behaviour are identified and qualitatively assessed. These relations are illustrated in the scheme in Figure 12. Blue elements represent static elements, and green elements represent dynamic elements.

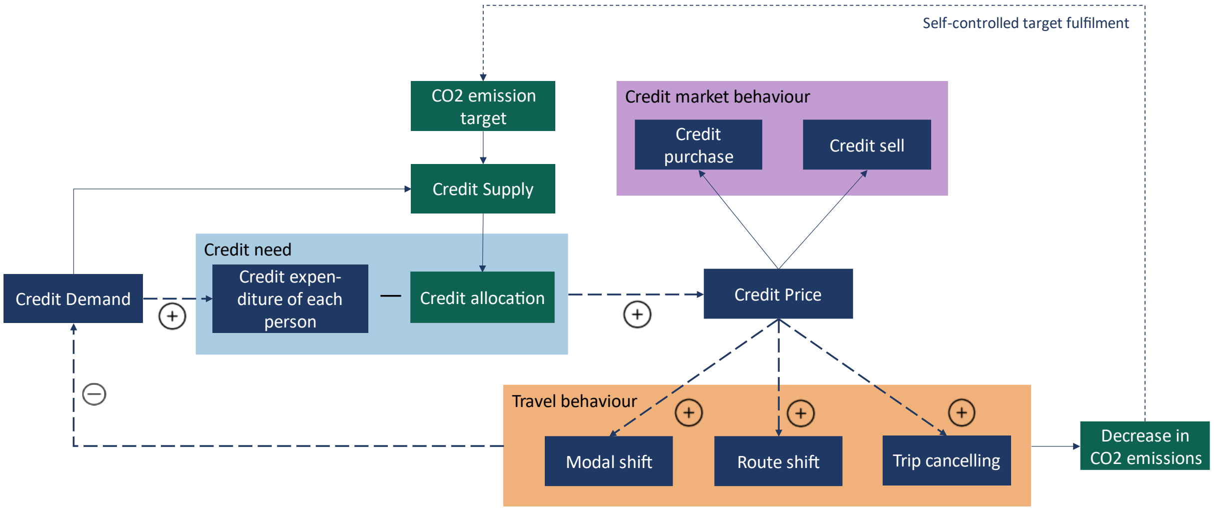


Figure 12: Behaviour elements and dynamics triggered by the implementation of the proposed TMC

In the following, the elements and the relations between the elements are explained, whereby elements shown in the scheme are in the first time in *italics*.

On the one hand, there is *credit demand*. Since one credit stands for a certain amount of CO_2 emissions, credit demand equals the total CO_2 emissions of the incorporated trips. Credit demand is *credit expenditure of each person* summed up over the whole population. On the other hand, there is *credit supply*. It equals the upper limit of CO_2 that is allowed to emit. Credit supply determines *credit allocation per capita*. *Credit need* of an individual person is the credit expenditure of that person minus the credit allocation. The credit need summed up over the whole population drives the credit price. The credit price is therewith dependent on the credit demand and credit supply but only changed by credit demand since credit supply is initially determined and therefore static.

One the one hand, the credit price influences people's behaviour in the credit market. If the credit price is high, people will tend to *sell credits*. If the credit price is low, they will tend to *purchase credits*. On the other hand, the credit price drives travel behaviour. Three potential behaviour changes have been identified. Firstly, people could change the travel mode (*modal shift*) from modes with high CO_2 emissions to modes with lower CO_2 emissions, for example from air to rail. Secondly, people could choose a destination which is closer to their origin (*route shift)*. For example, Dutch people could go on holiday to France instead of to Portugal. Thirdly, people could *cancel trips* and stay at home. The higher the credit price, the larger the incentive to use fewer credits and therefore the higher the magnitude of these travel behaviour changes will be.

Travel behaviour, influenced by the credit price, determines credit demand. The higher the modal shift, route shift and trip cancellation rate, the lower the credit demand will be. Therewith, a loop has been identified (indicated with dotted arrows in Figure 12). All relations of the loop are positive (an increase of the preceding element induces an increase of the subsequent element), except for one: an increase in the behavioural change leads to a decrease in credit demand. Hence there is an uneven number of negative relations which means that it is a balancing loop. Therefore, after some time credit demand, credit price and travel behaviour change will reach an equilibrium state. This equilibrium can change over time due to external factors. Such factors can be technological progress, which would lead to a decrease in credit demand because a trip would cause fewer emissions and therefore require fewer credits. Another factor can be the situation of the economy. For example, in booming times people would be willing to pay more for travelling which would increase the credit price.

For simplification, it is decided that this thesis focuses on modal shift and trip cancellation. Quantifying the route shift would require far-reaching knowledge about people's preferences. Hence, it is assumed the emission reductions happen because of modal shift and trip cancellation only.

3.3. Mode Choice Model

Based on the insights gained from the analysis of the behaviour elements and dynamics, the structure of the mode choice model is generated. The model consists of six interconnected steps. They are executed consecutively, while a prior step's output serves as input for the subsequent step. A simplified structure of the model is illustrated in Figure 13.

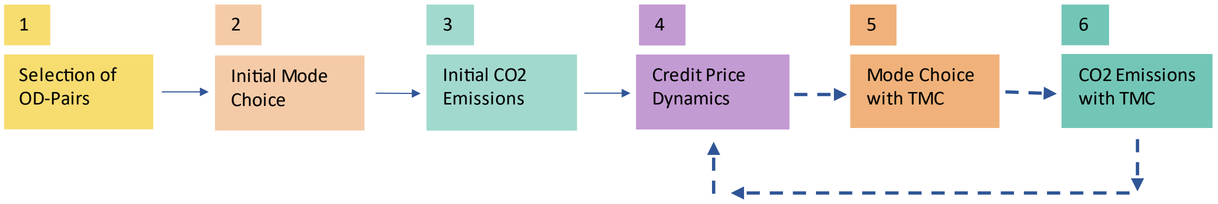


Figure 13: Simplified structure of the model with 6 steps

In the first step, a set of origin-destination-pairs (OD-pairs) is selected. This selection depends on the application of the model and is therefore further described in the case study in chapter 4.3. In the second step, the initial modal split (today's situation without any TMC implementation) is estimated for the selected OD-pairs. Therefrom, the initial CO_2 emissions (today's situation) are derived. Step 4 contains the implementation of the impacts of the TMC. In step 5, the modal split under the TMC is estimated. From that, the CO_2 emissions under the TMC are calculated (step 6). Therewith, the CO_2 emissions have changed, which leads to a change in the credit price. This is modelled by creating an interconnection between the CO_2 emissions (step 6) and the credit price dynamics (step 4). A loop is created. The model iterates for steps 4, 5 and 6.

Figure 14 shows a more detailed structure of the model. Blocks in light blue represent initial input elements. Blocks in dark blue represent process elements and output elements. They are generated by the model. Arrows represent the interconnections between the elements. By following the dotted arrows, the iteration path can be recognized. In the following sections, the complete methodology of the herewith presented mode choice model is presented.

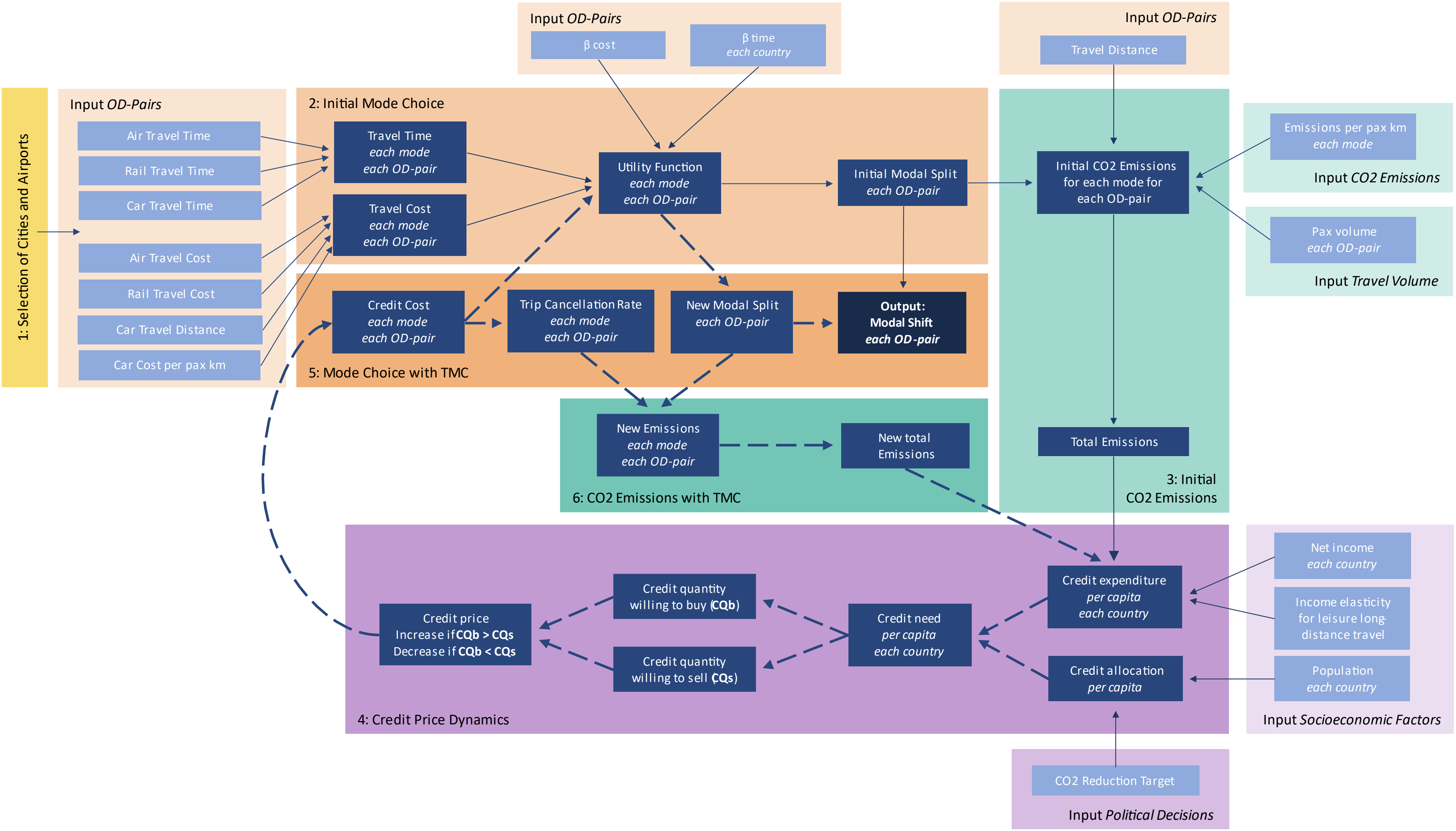


Figure 14: Detailed structure of the model

3.4. Mode Specification

Long-distance trips can be undertaken on water, land or air. For intra-European long-distance travelling, water transport can be neglected. Donners (2016) state car, bus, high-speed train, conventional train and plane as relevant. Analogue to Grolle (2020), it is decided to exclude the bus option because it is not very competitive for distances of more than 200 km. It is chosen to not distinguish between high-speed train and conventional train because the CO_2 emissions are nearly the same for both train types (see section 2.3.5). So, a modal shift between these two train types does not significantly influence the emissions. Also, the TMC instrument practicability would be difficult, because travellers often do not know and consciously choose the train type.

Consequently, air, rail and car are the considered modes in this study. In the following, they are characterised by trip properties, travel time components, travel cost components and CO_2 emissions. The trip properties include the detour factor, which is to be multiplied by the direct distance (Euclidean distance) to obtain the distance travelled. For the CO_2 emissions, it is decided to set the focus on WTW emissions. Thus, emissions of the whole energy chain are respected (see section 2.3.5).

3.4.1. Air Travel

Air travel time is composed of access time to the airport, waiting time at the airport, in-vehicle time and egress time from the airport. Access and egress times depend on the relative location of the airport to the city (assumed to be the traveller’s home). It is assumed that travels between the city and the airport happen by car. Waiting time at the airport (including baggage drop-off, security check, time to access the gate, waiting time at the gate and boarding time) is assumed to be 110 min (Grolle, 2020). In-vehicle time depends on the travel route. For flights with a transfer, the transfer time is included in the in-vehicle time.

The flight ticket price represents the travel cost. However, the ticket price can be delusive. Low-cost airlines can offer extremely cheap tickets, amongst others because they operate from decentral airports (for instance London Luton or Brussels South Charleroi). Therefore, it is chosen to also include the costs to get from the city to the airport and back. These costs are the distance between the airport and the city centre times the car operating costs per passenger per km of 0.326 €/km (see explanation in section 3.4.3).

Milieu Centraal et al. (2015) specify CO_2 emissions of 0.297 for regional flights (less than 700km) and 0.200 kg CO per passenger-kilometre for European flights (more than 700 km). To avoid an abrupt change of emissions at 700 km, it is decided to linearly decrease the emissions per passenger-kilometre from 0.297 for 400 km to 0.200 for 1.000 km. Hence, emissions per passenger-kilometre are calculated as follows:

$$em_{<400km} = 0.297kg\ CO2$$

$$em_{400-1.000km} = 0.297\ kg\ CO_2 - (0.297\ kg\ CO_2 - 0.200\ kg\ CO_2) \cdot \frac{(d - 400km)}{1.000km - 400km}$$

$$em_{>1.000km} = 0.200\ kg\ CO2$$

Equation 1: Air travel emissions

To incorporate all trip emissions, the car emissions of 0.116 kg CO_2 per passenger-kilometre (see section 3.4.3) of accessing and egressing the airport are added to the emissions above.

Table 3 shows an overview of the air travel specifications.

Table 3: Air travel specifications – Trip properties, travel time components, travel cost components and CO_2 emission components. In-vehicle time includes transfer times, d stands for distance.

Trip Properties		**Travel Time Components**		**Travel Cost Components**		**CO_2 Emission Components (WTW)**	
Factor	**Value**	**Factor**	**Value**	**Factor**	**Value**	**Factor**	**Value [kg CO_2 / pkm]**
Detour Factor	1.0	Access	Var.	Ticket Price	Var.	d <= 400km	0.297 [2]
		Waiting	110 min[1]	Access	d * 0.326 €/km	d >= 1,000km	0.200 [2]
		In-vehicle	Var.	Egress	d * 0.326 €/km	400km < d < 1,000km	0.297 – 0.200
		Egress	Var.			Access & egress	0.116

[1] *(Grolle, 2020)*

[2] *(Milieu Centraal et al., 2015)*

3.4.2. Rail Travel

For rail, Grolle (2020) chose a detour factor of 1.09. It is seen as too low by the author of this thesis. Therefore, for ten important routes regarding travel demand which are viewed as representative, air and rail distances are calculated with help of Brenschede (2022) and Google (2022). The resulting average detour factor is 1.3. This value is seen as reasonable and therefore used for determining the distances of rail connections.

Rail travel time is composed of access time to the station, waiting time at the station, in-vehicle time and egress time from the station. Since stations are usually centrally located, access and egress times are both assumed to be 20 min. Waiting time is assumed to be 15 min (Grolle, 2020). Analogue to air travel, in-vehicle time depends on the travel route, and transfer times are therein incorporated.

The train ticket price represents the travel cost. Access and egress costs are neglected because stations are usually located in the centre so they can be accessed cheaply by urban public transport.

Milieu Centraal et al. (2015) state WTW emissions of 0.031 kg CO_2 per passenger-kilometre for intercity trains and 0.026 for high-speed trains. Since there is a mix of these train types operating in the TMC perimeter, an average value of 0.029 kg CO_2 per passenger-kilometre is assumed. For the reason of the centrality of the station, the emissions of access to and egress from the station are ignored.

Table 4 shows an overview of the rail travel specifications.

Table 4: Rail travel specifications – trip properties, travel time components, travel cost components and CO_2 emissions. In-vehicle time includes transfer times.

Trip Properties		**Travel Time Components**		**Travel Cost Components**		**CO_2 Emissions (WTW)**	
Factor	**Value**	**Value**	**Value**	**Factor**	**Value**	**Train Type**	**Value [kg CO_2 / pkm]**
Detour Factor	1.3	Access	20 min	Ticket Price	Var.	HST and IC mixed	0.029 [2]
		Waiting	15 min[1]				
		In-vehicle	Var.				
		Egress	20 min				

[1] *(Grolle, 2020)*

[2] *(Milieu Centraal et al., 2015)*

3.4.3. Car Travel

The detour for car travel is chosen to be 1.2, according to Grolle (2020). It seems reasonable that car travel is slightly more direct than rail travel because detours to other cities for transferring are not required if travelling by car. A vehicle occupancy of 1.9, which has been identified in section 2.3.5, is assumed. The fuel consumption of a car is derived as follows: The average age of cars in the EU is 11.8 years. The officially specified fuel consumption of new cars in 2011 – which is the average manufacturing year of a car in the study year 2023 – was 5.3 litres per 100 km (Autoalan Tiedotuskeskus, 2022). Fontaras et al. (2017) compared laboratory and real-world emissions from passenger cars in Europe and found that real-world fuel consumption is about 1.5 to 2 litres per 100km higher on average. Therefore, the fuel consumption of a car is assumed to be 7 litres per 100 km. It is assumed that car travellers own a car and can therefore depart from home whenever they want. Therefore, access, waiting and egress time is zero, and total travel time equals in-vehicle time.

For simplification, the travel cost for car is assumed to be the sum of fuel cost and toll cost. It is chosen to only include the variable costs but not the fixed costs. It is known that people often do not incorporate the monthly fixed cost in their mode choice because it is a sunk cost (already paid at the beginning of the month), and people are not conscious of the value loss of the car per driven kilometre. For the fuel cost, it is assumed that half of the fuel is tanked up in the origin country and half in the destination country. As stated by Discover Cars (2021) as an average, the toll cost is assumed to be 0.06 € per km. A country-specific toll cost would go beyond the scope of this thesis because it would require the incorporation of toll costs of each country and the distance driven in each country on every route.

Therefore, the car travel cost TC_{car} is calculated as follows:

$$TC_{car} = \frac{\left(\frac{FuelCost_a + FuelCost_b}{2}\right) \cdot FuelCons + TollCost}{Occ} \cdot distance$$

Equation 2: Travel cost for car

Where:

$FuelCost_a$	Fuel price in origin country a
$FuelCost_b$	Fuel price in destination country b
$FuelCons$	Fuel consumption of the car per km
$TollCost$	Toll fee per vehicle per km
Occ	Car occupancy

Table 5 shows an overview of the car travel specifications.

Table 5: Car travel specifications – trip properties, travel time components, travel cost components and CO_2 emissions.

Trip Properties		**Travel Time Components**		**Travel Cost Components**		**CO_2 Emissions (WTW)**	
Factor	**Value**	**Factor**	**Value**	**Factor**	**Value**	**Factor**	**Value [kg CO_2 / km]**
Detour factor	1.2[1]	Access	0	Fuel	Var.	per veh-km	0.220[4]
Vehicle occupancy	1.9[2]	Waiting	0	Toll	0.06 €/km[3]	Per pkm	0.116
Fuel consumption	7lt / 100km	In-vehicle	Var.				
		Egress	0				

[1] (Grolle, 2020)

[2] *(BFS and ARE, 2017), (Reichert et al., 2016)*

[3] *(Discover Cars, 2021)*

[4] *(Milieu Centraal et al., 2015)*

3.5. Route and OD-Pair Connection Specification

This section specifies routes (OD-pairs) and OD-pair connections. From now on, the term OD-pair connection represents a route for one travel direction between two cities. The term route or OD-pair stands for the connections between two cities independent of the travel direction. Hence, a route between two cities (or one OD-pair) has two OD-pair connections (one in each direction).

3.5.1. Cities

City centres represent the starting point and ending point of a route. For rail, since the main station is usually in the city centre, the corresponding station is assigned to the city. For car, there is no assignment to the city required since the cities themselves are the starting and ending point of the route. For air, the procedure is explained in the following.

3.5.2. Airport to City Assignment

Airports are usually not in the city centre and do not always belong to only one city. Some airports serve different cities. For instance, Brussels Airport serves Brussels as well as Gent. Some cities like Paris or London have several airports. Therefore, airports need to be assigned to cities. The methodology used is based on Grolle (2020). He used the access and egress times to define which airports are considered feasible options. For each city, he chose to consider every airport which has an access/egress time of fewer than 2.5 hours. This leads to a lot of airports for some cities, for example, ten airports for the city of Rotterdam. For simplification and to focus on the most relevant airports for each city, the maximum access/egress time is limited to one hour in this thesis.

3.5.3. Airport Choice

For each OD-pair connection where a city which has multiple airport options is involved, an airport choice is undertaken. For simplification, an all-or-nothing assignment is chosen. This means that the "best" airport will be chosen by all passengers travelling on that OD-pair connection. The "best" airport is the airport which holds the lowest generalised costs. For each OD-pair connection with more than one airport option at the origin or destination, the generalised costs of a trip are computed for each airport option as below. The calculation is based on the assumption that people use the car to travel from the city to the airport and vice versa.

$$G = TT \cdot VTT + TC = \frac{TT_{inveh} + TT_{acc} + TT_{egr} + TT_{wait}}{60} \cdot VTT + Ticket_{air} + tc_{car} \cdot (d_{acc} + d_{acc})$$

Equation 3: Generalised costs for airport connections

Where:

G	Generalised costs for an OD-pair connection
TT	Travel time
TC	Travel cost
TT_{inveh}	In-vehicle travel time (official flight time)
TT_{acc}	Access time from city to airport by car
TT_{egr}	Egress time from airport to city by car
TT_{wait}	Waiting time at the airport
$Ticket_{air}$	Ticket price
tc_{car}	Access and egress cost per passenger-kilometre by car
d_{acc}	Access distance from city to airport by car
d_{egre}	Egress distance from airport to city by car

For simplification, VTT and car costs per passenger-kilometre are assumed to be constant for all countries. For VTT, the average value of 11.82€ per hour is taken (Wardman et al., 2016). Access and egress costs by car are assumed to be 0.186€ per km (fuel cost of 1.80€ per litre, fuel consumption of 7 litres per 100km and toll cost of 0.06€ per km, see section 3.4.3). Table 6 shows the airport choice in the example of Brussels to Milan. Brussels has two feasible airports (Brussels Airport and Brussels South Charleroi Airport), and Milan has three feasible airports (Milano Malpensa, Milano Linate and Bergamo-Orio al Serio). Brussels to Milan via Brussels Airport and Bergamo-Orio al Serio Airport have the lowest generalised travel cost and are therefore chosen for that OD-pair connection. Note that these values are from the case study (chapter IV) and that the airport choice could be different if the ticket price was taken from another travel day.

Table 6: Selection of the preferred airport pair for the flight from Brussels to Milan

Origin Airport	Brussels			Brussels South Charleroi		
Destination Airport	Milano Malpensa	Milano Linate	Bergamo-Orio al Serio	Milano Malpensa	Milano Linate	Bergamo-Orio al Serio
Flight Time [min]	90	85	85	325	80	85
Access Time [min]	22	22	22	46	46	46
Egress time [min]	50	24	49	50	24	49
Waiting time [min]	110	110	110	110	110	110
Ticket Price [€]	54	61	28	74	130	27
Access distance [km]	11	11	11	44	44	44
Egress distance [km]	40	7	46	40	7	46
Generalised Travel Costs [€]	**117**	**112**	**91**	**194**	**191**	**101**
Selected?	✗	✗	✓	✗	✗	✗

3.6. User Specification

Every citizen living in a country within the TMC perimeter is assumed to be a user of the TMC. It does not matter whether someone undertakes long long-distance trips or not. Every person receives credits at the beginning of an allocation period and is therewith incorporated into the TMC. It is chosen that underage people are included as well, and the parents or legal guardians receive the credits for the children. However, this design choice is not relevant for the further process.

The model includes user activities and user characteristics. The user activities are the behaviour elements mentioned in section *3.2*– receiving credits from the central authority, travelling resp. spending credits, and buying and selling credits. Every user has characteristics: Purpose of undertaking trips, nationality, net income, credit expenditure (which equals the CO2 emissions of the undertaken long-distance trips) and timing of booking.

This study focuses on leisure trips. The reduction to one travel purpose is done because leisure and business travellers are completely different travellers and need therefore be modelled differently (strongly deviating parameter values, for instance, VTT). Therefore, the purpose of every undertaken trip is leisure, independent of the user. The reasons to focus on leisure purpose are the following:

- With around 80%, leisure travellers hold by far the largest share of travellers of long-distance trips (see section 2.3.2)
- For leisure trips, the travellers bear the costs themselves. The choice maker and the traveller is the same person. For business travellers, it can be that the traveller makes the mode choice, and the company pays for the trip.
- The cost perception for business trips can additionally be distorted by the tax system: “In many countries, the expenses of business travel are a deductible item from the taxable income of business organizations. In effect, the costs of business travel are subsidised by governments. (…) Leisure travel expenses paid by individuals cannot be claimed as deductions against their personal income taxes.” (Leiper et al., 2008)

For the last two reasons, as the traveller does not bear (all) the costs, the mode choice can be less rational, and therefore difficult to model. On the contrary, leisure travellers are directly faced with benefits and costs caused by the TMC and its impacts on the cost. Therefore, it is expected that estimating the impacts of a TMC for leisure trips leads to more meaningful results.

For simplification, it is assumed that all users of the same nationality have the same net income, which is the average net income of citizens of the particular country. Also, all users of the same nationality have the same credit expenditure. The methodology for determining the credit expenditure per user is described later in section 3.10.1). Consequently, the number of different users equals the number of countries. With the inclusion of these user characteristics, different travel behaviours can be incorporated into the model.

For collecting flight and train ticket prices for the model, a decision must be made about the number of days between booking and departure. Therefore, the study of Wen and Chen (2017) is consulted (compare section 2.3.3). From Figure 7 it can be derived that the median booking time before departure is between 70 and 35 days, depending on the trip purpose. Both trip purposes are represented by about 50% of the dataset. Therefore, it is chosen to take an averaged time span of 45 days (1.5 months) between booking and departure. The timing of booking does not vary between users.

Table 7 shows an overview of the user specifications.

Table 7: User specifications – user activities and user characteristics

User Activities	User Characteristics	
Action	**Attribute**	**Value**
Receiving credits	Trip purpose	Leisure
Spending credits (travelling)	Nationality	Var.
Buying credits	Net income	Var. (related to nationality)
Selling credits	Credit expenditure	Var. (related to income)
	Timing of booking	45 days in advance

3.7. Utility Functions

The utility is calculated for each OD-pair connection and each mode to later estimate the modal split. This section as well as the next section (3.8) belong to step 2 in Figure 13 and Figure 14.

On the one hand, the Literature Review has shown that travel time and travel cost are the most significant variables for long-distance mode choice. On the other hand, it has been shown that studies on the influence of variables in long-distance travel are rare (see section 2.3.1). Therefore, it is difficult to find parameters that fit well in the context of this thesis. Consequently, it is chosen to express utility as a composition of travel time and travel cost. Other quality variables like the number of interchanges, comfort, frequency and all background variables are neglected (besides trip purpose which is only leisure).

Accordingly, the utility function is composed of beta for travel time times travel time plus beta for travel cost times travel cost. The composition of travel time and travel cost has been determined in section 3.4. Therewith, the utility functions can be defined for air, rail and car of each incorporated city pair:

$$U_{ij,m} = \beta_{time} \cdot TT_{ij} + \beta_{cost} \cdot TC_{ij}$$

Equation 4: Utility function

Where:

$U_{ij,m}$	Utility for mode m for travelling from city i to city j
β_{time}	Weight of travel time
TT_{ij}	Travel time from city i to city j
β_{cost}	Weight of travel cost
TC_{ij}	Travel cost for travelling from city i to city j

With β_{time} and β_{cost}, the VTT can be determined:

$$VTT = \frac{\beta_{time} \cdot 60}{\beta_{cost}}$$

Equation 5: VTT

It is decided to use values from Koppelman and Wen (2000) for β_{time} and β_{cost} (-0.0099 for β_{time} and -0.0461 for β_{cost}). The reason to choose for this study is that VTT resulting from these values is 12.89 € per hour, which coincides well with the average VTT for “other trips” (assumed to represent leisure purpose, not commuting and business) of 11.82 found by Wardman et al. (2016) in their large scale meta-analysis for Europe. As VTT is strongly dependent on the regional context (see section 2.3.8), it is decided to make it country related. From a macroscopic view, the VTT for an area A can be expressed as follows (Hu et al., 2022):

$$VTT_A = \frac{GDP_A}{T_A \cdot PN_A}$$

Equation 6: VTT for area A (Hu et al., 2022)

Where:

GDP_A	Gross domestic product of area A
PN_A	Population of area A
T_A	Average working hours of the workers of area A

With Equation 6, the VTT is calculated for each country. To calibrate all calculated VTT_A values to 11.82 for leisure trips, all VTT_A values are multiplied with the ratio between 11.82 € per hour and the population weighed average of all VTT_A values:

$$VTT_{A\_calibr} = VTT_A \cdot \frac{11.82}{\sum_A VTT_A \cdot PN_A}$$

Equation 7: VTT for area A calibrated to leisure trips

Therewith, VTT has been determined for leisure trips depending on the country. It is assumed that all travellers between two cities have their origin in the countries of these cities. Furthermore, it is assumed that the share of the traveller's nationality equals the share of the population of the origin and destination country. E.g., Switzerland has half of the population of the Netherlands. Hence, two-thirds of travellers between Zurich and Amsterdam are assumed to be Dutch and one-third to be Swiss. Therewith the average VTT for trips between city i in country a and city j in country b can be calculated:

$$VTT_{ab} = VTT_{a\_calibr} \cdot \frac{PN_a}{PN_a + PN_b} + VTT_{b\_calibr} \cdot \frac{PN_b}{PN_b + PN_b}$$

Equation 8: VTT for leisure travel between countries a and b

By putting together Equation 5 and Equation 8, β_{time}can be expressed for each OD-pair connection with origin country a and destination country b:

$$\beta_{time,a,b} = \frac{GDP_a}{T_a \cdot PN_a} \cdot \frac{PN_a}{PN_a + PN_b} + \frac{GDP_b}{T_b \cdot PN_b} \cdot \frac{PN_b}{PN_b + PN_b}$$

Equation 9: Beta-Time for leisure travel between countries a and b

This $\beta_{time,a,b}$ is used for the utility function (Equation 4).

3.8. Logit Model

The modal shares for air, rail and car are calculated with a logit function. The above-calculated utilities are inserted in Equation 10.

$$P_m = \frac{e^{U_{ij,m}}}{\sum e^{U_{ij,m}}}$$

Equation 10: Logit function

Where:

P_m	Probability of choosing mode m (= modal share of mode m)
$U_{ij,m}$	Utility for mode m for travelling from city i to city j

The sum of P_{air}, P_{rail} and P_{car} equals 1 for all city pairs. Therewith, the initial modal share – the situation nowadays without a TMC – is estimated for the considered city pairs. Step 2 of Figure 13 and Figure 14 is therefore completed.

3.9. CO$_2$ Emissions

This section explains the methodology of step 3 in Figure 13 and Figure 14. As the modal share is calculated for each city pair, the emissions can be determined by incorporating the passenger volume for each city pair. The total CO$_2$ emissions of all regarded trips are the sum of emissions of each mode. The emission of a mode is the multiplication of passenger volume, modal share, travel distance and emissions per passenger-kilometre, summed up for all city pairs:

$$EM = \sum_{ij} EM_{ij,air} + \sum_{ij} EM_{ij,rail} + \sum_{ij} EM_{ij,car} =$$

$$\sum_{ij} V_{ij} \cdot (P_{ij,air} \cdot d_{ij,air} \cdot em_{ij,air} + P_{ij,rail} \cdot d_{ij,rail} \cdot em_{rail} + P_{ij,car} \cdot d_{ij,car} \cdot em_{car})$$

Equation 11: Total CO$_2$ emissions

Where:

EM	Total CO$_2$ emissions
$EM_{ij,m}$	CO$_2$ emissions for all trips of mode m from city i to city j
V_{ij}	Passenger volume from city i to city j
$P_{ij,m}$	Modal share of mode m from city i to city j
$d_{ij,m}$	Travel distance from city i to city j with mode m
$em_{ij,m}$	CO$_2$ emissions per passenger-kilometre from city i to city j with mode m

The values for the emissions per passenger-kilometre are described in section 3.4). The values for rail and car are independent of the city pair. The values for air depend on the distance – the higher the distance the lower the emissions per kilometre (see section 3.4.1). Therewith, step 3 of Figure 13 and Figure 14 is completed.

3.10. Credit Price Dynamics

This section corresponds to step 4 of Figure 13 and Figure 14. In the following, the computation of credit expenditure, credit allocation, credit need and credit price are specified. Then, the impacts of the TMC on mode choice, travel demand (trip cancellation) and CO_2 emissions are specified.

3.10.1. Credit Expenditure

Section 3.9 explicated the computation of the total emissions EM from all trips incorporated in the model. Since it was decided that emitting one ton of CO_2 requires the expenditure of one credit (see section 3.1.3), the total credit expenditure is equivalent to the total emissions in tons. Hence, total credit expenditure is known at this moment. In the following, the methodology to obtain the credit expenditure per user from the total credit expenditure is explained.

It is decided to not apportion the total credit expenditure among citizens of countries where the trips incorporated into the model start and end. Otherwise, the choice of routes which are included in the model would influence the credit expenditure of a country. For instance, if 100 routes included in the model have their origin in the Netherlands, but only 10 in Portugal, citizens of the Netherlands would have a far higher credit expenditure than citizens of Portugal, only because of the choice of the set of routes included in the model. Therefore, total credit expenditure is distributed to all users as follows:

In section 2.3.4 it was identified that GDP per capita and therewith average income is the factor which influences the most how frequently someone travels long-distance for leisure purpose. Based on the assumptions that CO_2 emissions increase proportionally with the frequency of long-distance trips (no national differences in distances, modal split, or type of vehicle), it is therefore assumed that differences in credit expenditure between citizens of different countries are only caused by differences in net income. To quantify the differences in credit expenditure, it is chosen to use income elasticity of demand. The income elasticity of demand describes how a change in income affects demand. Following the definition of elasticity, income elasticity of demand e_{inc} can be expressed as follows:

$$e_{inc} = \frac{\%\ variation\ in\ credit\ expenditure}{\%\ variation\ in\ income} = \frac{(CE_a - CE_{avg})/CE_{avg}}{(INC_a - INC_{avg})/INC_{avg}}$$

Equation 12: Income elasticity of demand

Where:

e_{inc}	Income elasticity
CE_a	Credit expenditure per capita in country a
CE_{avg}	Average credit expenditure per capita (all countries)
INC_a	Net income per capita in country a
INC_{avg}	Average income per capita (all countries)

In two surveys in Middle and Northern Europe, significant values for long-run income elasticity of 1.19 and 1.6 have been found (Christensen and Nielsen, 2017). It is chosen to take an averaged value of 1.4. The CO_2 emissions of all incorporated trips divided by the population of all incorporated countries represent the average credit expenditure per capita for all countries. Therewith, the credit expenditure per capita can be calculated for each country by solving the equation:

$$CE_a = e_{inc} \cdot \left(INC_a - INC_{avg}\right) \cdot \frac{CE_{avg}}{INC_{avg}} + CE_{avg}$$

Equation 13: Credit expenditure per capita of country a

3.10.2. Credit Allocation

The total credit supply per year depends on the CO_2 emission reduction target which wants to be achieved with the TMC. The reduction target can be chosen by the user of the model. Hence, the total credit supply S is determined as follows:

$$S = (100\% - TG) \cdot EM$$

Equation 14: Credit supply

Where:

S	Total credit supply
TG	Emission reduction target [%]
EM	Total CO_2 emissions (total credit expenditure) before incorporating the TMC

As long as the emission target is not changed by politics, supply is constant. Since it was chosen for an equal credit allocation to all citizens within the TMC perimeter, credit allocation CA (number of credits allocated per person) equals the total supply divided by the population size:

$$CA = \frac{S}{PN} = \frac{(100\% - TG) \cdot EM}{PN}$$

Equation 15: Credit allocation

Where:

CA	Credit allocation
PN	Population within the TMC perimeter

In the model, credit allocation is set as a constant – it is assumed that the emission target is not changed by the politic. In reality, it could change marginally over time if population size changes.

3.10.3. Credit Need

The credit need describes the gap between the credits a user spends and the credits allocated to the user. Therefore, the individual credit need for a citizen of origin country a (CN_a) can be expressed as follows:

$$CN_a = CE_a - CA$$

Equation 16: Credit need per capita of country a

This results in countries of citizens with a credit shortage ($CN_a$of each citizen of that country is positive) and in countries of citizens with a credit surplus ($CN_a$of each citizen of that country is negative). The firsts are expected to buy credits from the latter. The sum of the credit need of all citizens with a positive value is named *credit quantity willing to buy* (CQb) and is the demanded credits in the market. The sum of the credit need of all citizens with a negative value is named *credit quantity willing to sell* (CQs). This represents the credits in the market which are offered to sell. This is based on the assumption that all people who have an excess of credits sell their credits and do not conserve them.

3.10.4. Credit Price

As explored in section 3.2, the credit price will approach an equilibrium. The macroeconomic theory says that the price is high if demand is high and supply is low, and the price is low if demand is low and supply is high. Since supply is constant in the model, the price only depends on demand. Figure 15 qualitatively shows the supply and demand curves. With the incorporation of the TMC the emissions decrease from the point where the demand curve intersects with the x-axis (credit price = 0) to the point where the demand curve intersects with the supply curve.

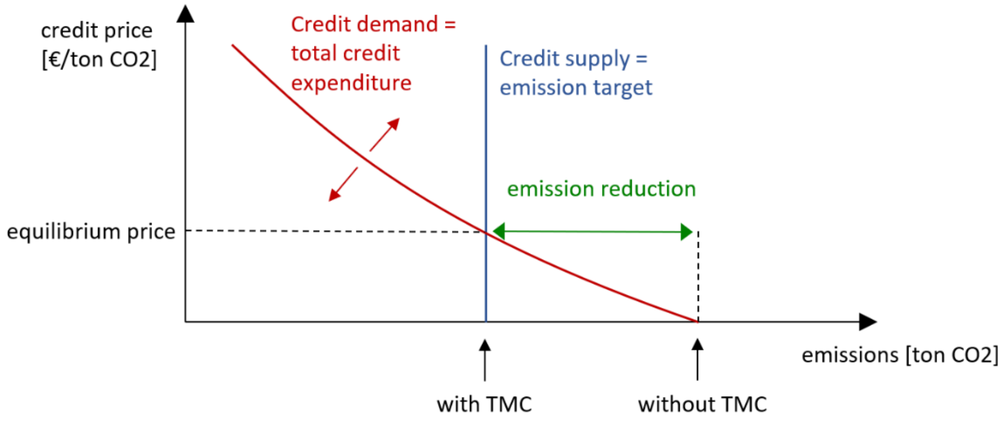


Figure 15: Supply and demand of credits determine the equilibrium credit price

To find the equilibrium price, the following decision criterium is applied: If *credit quantity willing to buy* (CQb) is bigger than *credit quantity willing to sell* (CQs), the credit price needs to be increased. This is the case if credit request is higher than credit availability in the market. Otherwise, if *credit quantity willing to buy* is smaller than *credit quantity willing to sell*, the credit price needs to be decreased. This happens when credit request is lower than credit availability. In reality, the central authority is responsible for steadily adjusting the credit price: If *credit quantity willing to buy* is bigger *than credit quantity willing to sell*, the credit price needs to be increased, otherwise decreased. The goal is that both quantities are always in balance. In the model, Equation 17 is used to get from credit price p of the previous iteration to the new price p_{new} of the following iteration:

$$p_{new} = p + 100 \cdot (CQb - CQs)$$

Equation 17: Credit price

This formula was found to get to a reasonable approximation of the equilibrium price (the equilibrium price will be obtained by iterating steps 4 to 6, see Figure 13 and Figure 14). Before the first iteration, p is set to 0. In the first iteration, CQb minus CQs is always a positive value which means that p_{new} will become a value bigger than 0.

This methodology is based on two assumptions. First, it is assumed that the market clears at all times. All credits on the market are always traded so that there are no leftover credits on the market. Second, it is assumed that people spend all credits until the period ends and the allocation is repeated. Policy-wise, this can be achieved by introducing a law saying that credits expire at the end of each period. Therewith, credit stockpiling is avoided.

In step 2 (Figure 13 and Figure 14) the initial modal share without a TMC was estimated. Next, the TMC will be incorporated into the mode choice model, considering the herewith obtained credit price. The TMC will have impacts on travel behaviour. As decided in section 3.2, the focus lies on the induced modal shift and the change of total travel demand, embodied by trip cancellation. The next two chapters explicate the impacts on mode choice and trip cancellation. They correspond to step 5 of Figure 13 and Figure 14.

3.10.5. Impacts on Mode Choice

At this stage, the impact on the modal shift is determined. Therefore, the TMC is incorporated into the mode choice model and the modal split under the TMC is estimated.

The calculated credit price (p_{new}) is incorporated into the utility function by adding the **credit costs** of the trip (credit price times required credits for the trip) to the travel costs:

$$U_{ij,m} = \beta time_{a,b} \cdot TT_{ij,m} + \beta cost \cdot (TC_{ij,m} + \boldsymbol{p_{new}} \cdot \boldsymbol{d_{ij,m}} \cdot \boldsymbol{em_{ij,m}})$$

Equation 18: Utility under TMC (1)

Combing the initial travel cost with the credit cost leads to

$$U_{ij,m} = \beta time_{a,b} \cdot TT_{ij,m} + \beta cost \cdot TC_{ij.m,TMC}$$

Equation 19: Utility under TMC (2)

Where:

$U_{ij,m}$	Utility for travelling from city i to city j with mode m
$\beta time_{ab}$	Weight of travel time for travelling from country a to country b
$TT_{ij,m}$	Travel time from city i to city j with mode m
$\beta cost$	Weight of travel cost
$TC_{ij,m}$	Travel cost for travelling from city i to city j with mode m without TMC
$d_{ij,m}$	Travel distance from city i to city j with mode m
$em_{ij,m}$	CO_2 emissions per passenger-kilometre from city i to city j with mode m
$TC_{ij,m,TMC}$	Travel cost for travelling from city i to city j with mode m under TMC (sum of initial travel cost and cost for the credits)

This methodology gives the impression that credits always need to be bought in the market. This is not the case because earlier it was determined that everybody gets a certain number of credits for free. However, for the following reason, it is decided to always add up the credit costs of a trip, no matter if the user is buying the credits on the market or still has the credits available from the allocation: Users always experience a credit cost for travelling because if they did not travel, they could sell their credits. In other words, they miss revenue by not selling them. Therefore, spending credits which do not have to be bought are also considered as a cost. Then, the logit model (see section 3.8) is fed with these utilities and the modal split under the TMC is estimated. Subtracting the modal split estimated in step 2 (Figure 13 and Figure 14) results in the modal shift induced by the TMC.

3.10.6. Impacts on Trip Cancellation

Next, after estimating the modal split under the TMC, the impacts on total travel demand are determined. Therefore, the trip cancellation rate is calculated by using price elasticity of demand. Price elasticity of demand describes how a change in price affects demand. The elasticity equals the ratio of the percentage change in quantity demanded of a product to the percentage change in price (Investopedia Team et al., 2022). Following the definition of elasticity, price elasticity of demand can be expressed as follows:

$$e_p = \frac{\%\ change\ in\ travel\ demand}{\%\ change\ in\ travel\ costs} = \frac{(V_{ij,m,TMC} - V_{ij,m})/V_{ij,m}}{(TC_{ij,m,TMC} - (TC_{ij,m})}$$

Equation 20: Price elasticity of demand

Where:

e_p	Price elasticity
$V_{ij,m}$	Passenger volume from city i to city j with mode m without TMC
$V_{ij,m,TMC}$	Passenger volume from city i to city j with mode m under TMC
$TC_{ij,m}$	Travel cost for travelling from city i to city j with mode m without TMC
$TC_{ij,m,TMC}$	Travel cost for travelling from city i to city j with mode m under TMC

$V_{ij,m}$ equals the modal share of mode m times the passenger volume of that OD-pair connection. Therewith, the new passenger volume (volume under the TMC) can be calculated for each mode and city-pair by solving the equation:

$$V_{ij,m,TMC} = e_p \cdot \left(TC_{ij,m,TMC} - TC_{ij,m}\right) \cdot \frac{V_{ij,m}}{TC_{ij,m}} + V_{ij,m}$$

Equation 21: Elastic demand

By dividing the passenger volume difference between without and with TMC ($V_{ij,m} - V_{ij,m,TMC}$) by the passenger volume without TMC ($V_{ij,m}$), the trip cancellation rate is determined for each mode and city-pair. To conclude, the increase in travel costs due to the addition of credit costs leads to passengers cancelling the trip.

Elasticity values are taken from de Bok et al. (2010). They estimated a mode choice model for long-distance travel in Portugal and found elasticity and cross-elasticity values for both cost and travel time for car, bus and rail, for the trip purposes of commuting, business and other. To determine the travel demand change, it is decided to consider the elasticity values for cost and to leave out the values for time and all cross-elasticity values. Travel time does not change under the TMC, and cross-elasticity describes the substitution of products which is already covered by the modal shift. Since air is missing in the study of de Bok et al. (2010), it is chosen to take the average of car cost elasticity (-0.278) and rail cost (-0.544), which makes a price elasticity of demand of -0.411. The values refer to the trip purpose *other* and therefore best represent leisure travel.

3.10.7. Impacts on CO_2 Emissions

As the new modal split and the new passenger volume (with the incorporation of the TMC) are determined, the new total CO_2 emissions can be derived. This section refers to step 6 in Figure 13 and Figure 14. By inserting the modal shares estimated in section 3.10.5 and the travel demand estimated in 3.10.6 into Equation 11 (see section 3.9), the total CO_2 emissions under the TMC are determined.

At this stage, the first iteration is completed. The second iteration starts by going back to step 4 (see Figure 13 and Figure 14). Since emissions equal the total credit expenditure, the total credit expenditure is updated by using the new total emissions (total emissions under the TMC). The loop including steps 4 to 6 is repeated until the credit price reaches an equilibrium, which means that p_{new} and p in Equation 17 do not significantly differ anymore, e.g. p_{new} divided by p is between 0.99 and 1.01. At this point, the credit price has reached an equilibrium which guarantees that the emission reduction target is precisely achieved.

IV. Case Study

In Chapter III, the TMC which is incorporated into the mode choice model was specified and the dynamic that the TMC triggers were analysed. Based on that, a structure of the mode choice model was developed, and the model specifications were explicated. The model is conceived for the continent of Europe.

This case study presents an application of the mode choice model for a perimeter within Europe for a selected set of OD-pairs. First, the perimeter of the TMC and the emission reduction target are defined. Then, a set of cities is selected, and airports are assigned to these cities. These are the cities for which the modal shift induced by the TMC will be estimated. Thereafter, the data collection is explained, and the data are analysed. The results of the case study will be presented in chapter V.

The year of interest in this case study is 2023, which is the year of the finalisation of this study. So, it is assumed that the TMC is implemented in 2023. The reference year is 2019, from which socioeconomic data are taken.

4.1. Perimeter of the TMC

The TMC proposed in this case study spans the European mainland and the United Kingdom. Since we are interested in the modal shift between air, rail and car, countries not on the mainland (Cyprus, Iceland, Ireland, Malta) are excluded. There is no alternative to air to access them except for boat travel, which is not within the scope of this study. If Cyprus, Iceland, Ireland and Malta were included, a large part of travellers would be forced to cancel trips since the credit supply is not sufficient so that everyone can continue flying as before. Accordingly, the countries participating in the TMC are:

Table 8: Countries participating in the TMC

EU countries	Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
EFTA countries	Norway, Switzerland
Others	Albania, Bosnia & Herzegowina, North Macedonia, Serbia, United Kingdom

4.2. Emission Reduction Target

The implementation of the TMC requires the politics to agree on an emission reduction target. The “2030 Climate target plan” foresees a GHG emissions reduction of 55% for 2030 compared to the 1990 level (see section 2.1). Therefore, in the following, it is chosen that emissions must be reduced by 45% by 2030 compared to the 1990 level. Between 1990 the emissions from transport increased by 27%, according to calculations based on data from European Environment Agency (2021). It is chosen that the percentual reduction between 2019 and 2030 is the same for every year. This implied that this yearly percentual reduction must be 9% in order to achieve the 55% reduction by 2030. This means that for 2023 – which is the year of interest in this case study – a reduction of 13% compared to 1990 and of 31% compared to the 2019 level is required. Figure 16 shows the allowed CO_2 emissions for each year, whereby the emissions of 1990 are 100%.

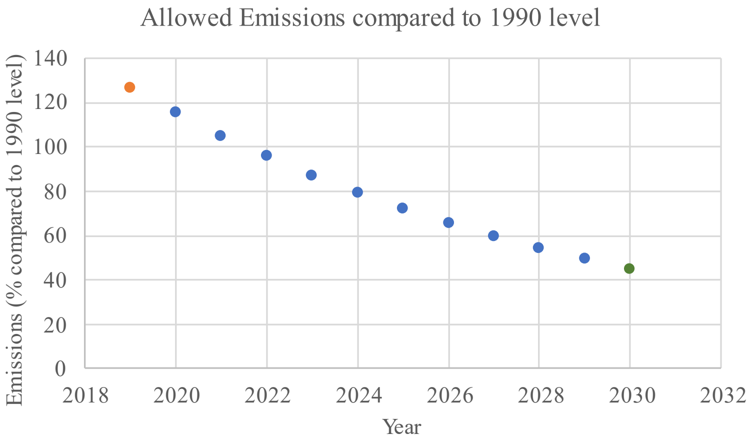


Figure 16: Allowed emissions compared to the 1990 level for each year. Orange dot: from data, green dot: directed by the "2030 Climate target plan", blue dots: interpolated between orange and green dots.

Consequently, the TMC in this case study foresees a credit supply which is 70% of the initial credit demand. This approximates the reduction target of 31% compared to 2019. The target choice is based on the assumption that emission reduction is achieved by TMC only – and no other measures (for instance other policy instruments, carbon removal technologies) are implemented. Additionally, it is also investigated how different reduction targets affect the credit price.

4.3. City and Airport selection

The goal of this case study is to achieve results which are as comprehensive as possible. Hence, a large set of major cities within the perimeter of the TMC is incorporated. Donners (2016) defined a selection of the most significant metropolitan areas for a high-level European Network. For the case study, this set is taken, but the following cities are removed because of several reasons:

- Dublin (Ireland): no rail connection to the mainland
- Minsk (Belarus), Tampere (Finland): not existing in rail ticket booking platform (trainline.com)
- Kiev (Ukraine): No ticket prices findable because of the political situation as of 2022/2023
- Kaliningrad, Moscow, St. Petersburg (Russia). Ankara, Istanbul (Turkey): not within the perimeter of the TMC

The set of OD-pairs is formed by connecting all the remaining cities with each other.

To obtain the selection of airports which are to be assigned to the selected cities, data from Grolle (2020) is used. He calculated the access/egress time between each city and each airport. By extracting all relations with an access/egress time lower than one hour, we know for each city which airports are feasible. Consequently, Plovdiv (Bulgaria), Ostrava (Czech Republique) and Rouen (France) are removed from the city set because there is no airport accessible within one hour. Thereafter, very small airports and airports mainly used for freight transport and business travel are removed due to their low importance for leisure travel (Antwerp International Airport, Liège Airport, Deauville-Saint-Gatien Airport, Groningen Airport). Consequently, the city of Groningen is also removed from the city set.

The following cities have multiple feasible airports: Brussels, Copenhagen, Grenoble, Montpellier, Strasbourg, Aachen, Dusseldorf, Karlsruhe, Cologne, Ruhrgebiet (Essen), Brescia, Milano, Rome, Katowice, Warsaw, Bilbao, Stockholm, Rotterdam, Utrecht, Birmingham, Glasgow, Leeds, Liverpool, London, Manchester, Newcastle Upon Tyne.

The following airports serve multiple cities:

- Brussels Airport: Antwerpen, Brussels, Gent, Liege
- Brussels South Charleroi Airport: Brussels, Liege
- Cologne-Bonn Airport: Cologne, Düsseldorf
- Saarbrücken Airport: Saarbrücken, Karlsruhe
- Milan Bergamo Orio al Serio Airport: Milano, Brescia
- Krakow John Paul II International Airport: Krakow, Katowice
- Amsterdam Airport: Amsterdam, Rotterdam, Utrecht
- Liverpool John Lennon Airport: Liverpool, Manchester

Finally, the selected set contains 112 cities and 124 airports. This yields $(112 - 1)^2 = 12{,}321$ OD-pair connections and $(124 - 1)^2 = 15{,}129$ airport pair connections. Since some airports serve multiple cities, there are in total $(144 - 1)^2 = 20{,}449$ connections. They are partially identical in the cities but not in the airports

4.4. Data Collection

In the next step, data are collected to conduct the case study. Table 9 provides an overview of the collected data and the sources. One part of the data origins from datasets and the other part is generated by web scraping. Web scraping stands for the automated extraction of data from a website using a script. First, the collection of data which origins from datasets is explicated. Second, the generation of data by web scraping is explained.

Table 9: Overview of collected data and its sources

Category	**Data**	**Source / Value**			
		General	**Air**	**Rail**	**Car**
Cities and Airports	Long/Lat coordinates of cities	*(Grolle, 2020)*			
	Distance between cities		Geodesic distance from coordinates	Direct distance times détour factor	*(Grolle, 2020)*
	Passenger volume	*(Grolle, 2020)*			
Trips	In-Vehicle time		Web scraping *(kiwi.com)*	Web scraping (trainline.com)	*(Grolle, 2020)*
	Access & egress time		*(Grolle, 2020)*	20 min	0 min
	Access & egress distance		*(Grolle, 2020)*	Not considered	0 km
	Ticket Price		Web scraping *(kiwi.com)*	Web scraping *(trainline.com)*	
Socioeconomics	Population for each country	(Eurostat, 2022a), *(The World Bank, 2022a)*			
	GDP	(Eurostat, 2022b)			
	Working hours	(Eurostat, 2022c)			
	Net income for each country	*(The World Bank, 2022b)*			
	Fuel price for each country	*(European Environment Agency, 2022)*			

4.4.1. Datasets

The data to characterise the cities and airports – latitude and longitude of cities, rail and car distance between cities, and passenger volume – are taken from Grolle (2020). Airport latitudes and longitudes are retrieved from Google (2022). Direct distance is calculated by a transformation of pairs of airport coordinates into the geodesic distance. For the passenger volume, Grolle (2020) did a demand estimation for city pairs. First, he obtained the air travel demand from revealed passenger data from the airline industry. Then, he expanded this data to total travel demand using a relatively sophisticated own methodology (see Appendix B), which is not further analysed in this study. Travel demand data are available for 8,443 out of the 12,321 incorporated OD-pair connections. OD-pair connections without travel demand are left out in this case study. Since the model of this thesis is based on leisure travel, this total travel demand is scaled down to the demand for leisure purpose. There is a lack of data about the share of leisure trips per OD-pair connection. Therefore, it is decided to simply assume that all OD-pair connections hold the same share of leisure travellers. In the literature review, it has been pointed out that leisure travellers represent 80% of all travellers (see section 2.3.2). Hence, the estimated travel demand is reduced by 20%. Figure 17 shows the demand for each city (the sum of all passengers departing from and arriving in a city in one year). The colour indicates if a city will later be considered (in turquoise) or not (in bright blue). The reason for not considering cities is that either no passenger volume was available, or no air or rail travel cost could be collected (see below, section 4.4.2).

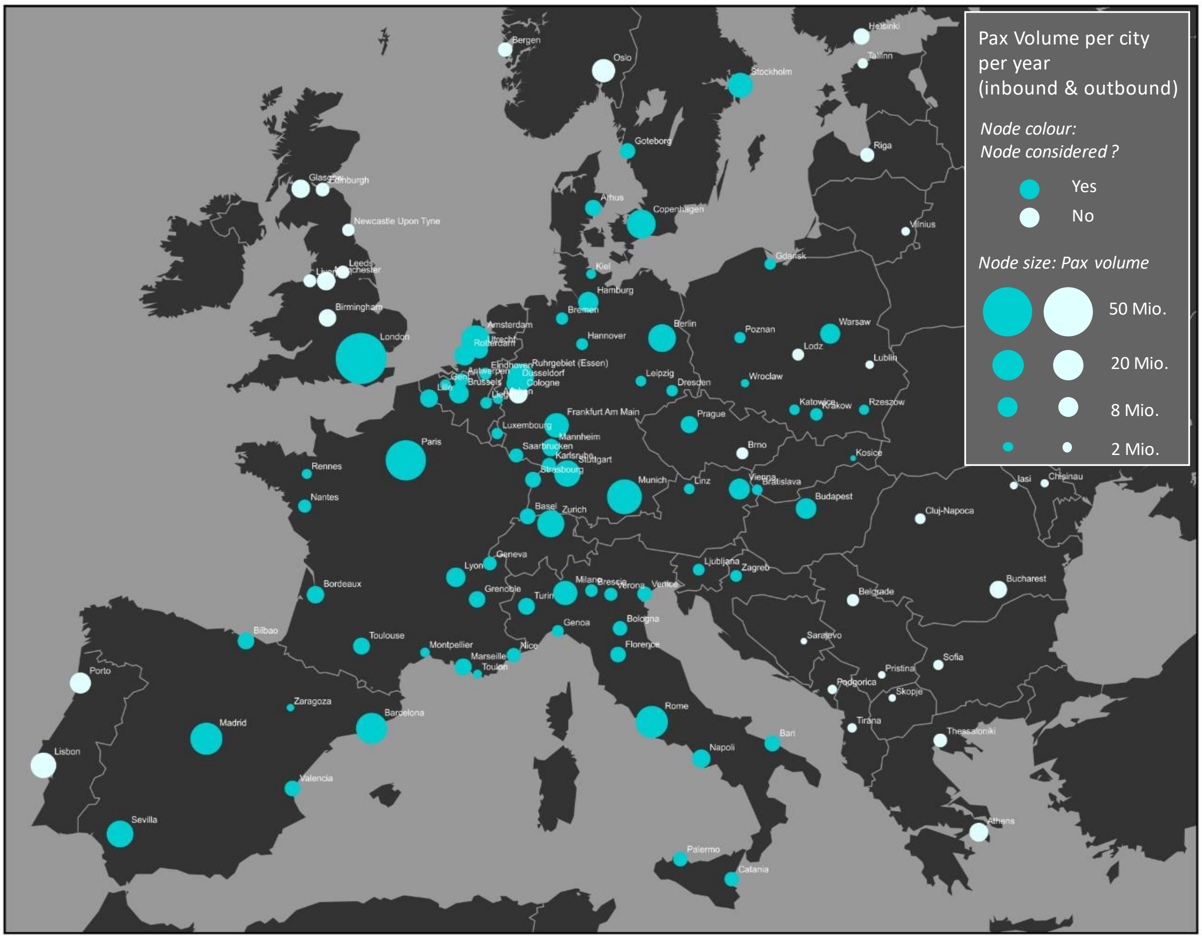


Figure 17: Yearly passenger volume for each city (sum of inbound and outbound)

For air travel, access and egress distance and time (city to airport and airport to city) are taken from Grolle (2020). For Valencia, Porto and Venice the values are missing, so they are taken from Google (2022). For rail and car, access and egress times are assumed to be 20 min and access and egress distances are not considered (see section 3.4). In-vehicle time for car is taken from Grolle (2020).

The socioeconomic data are gathered from 2019 datasets to avoid distortions caused by covid. Therewith, the population for each country from 2019 is taken from Eurostat (2022a) for EU countries and complemented with data from The World Bank (2022a) for non-EU countries. The average net income for each country is taken from The World Bank (2022b), the GDP from Eurostat (2022b) and the average working hours from Eurostat (2022c), all for the year 2019. To well compare the car travel costs with the travel costs of air and rail, the most recent (November 2022) fuel prices are taken from European Environment Agency (2022). Since fuel price data for Kosovo is missing, it is assumed that it is the same as in the neighbouring country Albania.

4.4.2. Web Scraping

Ticket costs for air and rail strongly depend on the travel day and time span between booking and the trip. Therefore, it is decided to use real ticket prices from booking platforms. As determined in section 3.6, we want the ticket prices as they are 45 days before departure. Due to the high number of OD-pair connections, web scraping is used to automate the process of data collection. In-vehicle time for air and rail is also collected by web scraping. Therewith, the time refers to the same trip as the ticket cost. For web scraping, the Selenium package – a tool to automate web browser interaction from Python – is used. The departure date is set to 20.12.2022, and the collection of the ticket prices is undertaken during the first half of November 2022. For air, it is chosen to use the booking platform kiwi.com. The platform aggregates fares from over 750 airlines (Wikipedia, 2022b). Other websites detect that web scraping is used and deny access (skyscanner.com, kayak.com, vliegtickets.nl), they exclude low-cost airlines (expedia.com), or they have a not comprehensible structure of the URL (Google Flights). Kiwi.com is chosen because these issues are not the case. Only direct flights and flights with one stop are regarded. Flights with more stops are not considered, because it is seen as improbable that people choose flights with more stops for a trip within Europe. The Python script iterates over all 15,129 combinations of airports. In each iteration, the URL is given over with the current origin and destination airport and city names and the date of the flight. For example, for a flight from Helsinki to Bremen on 20.12.2022 (no return flight, maximum one stop) the URL is the following:

*https://www.kiwi.com/us/search/results/**helsinki-helsinki-finland/bremen-bremen-germany/2022-12-20**/no-return?stopNumber=1~true*

The ticket price and travel time of the flight which the website proposes as the “best” option is extracted. This is done by using the XPath (XML Path Language) of the wanted element. With XPath, specific elements of an XML document can be addressed. Double-checking with all available options for a few searches has shown that the “best” option is reasonable. For more detailed information, Appendix C shows an illustration of the Kiwi website. For rail, it is chosen to use trainline.com. It is the booking platform incorporating the most railway operators, with over 270 rail and coach operators in 45 countries. Omio.com does not find ticket fares for many longer trips. Raileurope.com does not work since it denies access because it detects that web scraping is used. The process of scraping the rail ticket prices and travel times is identic to that of the flights. Instead of the city names, city codes are included in the URL. These codes are collected by manually searching for train connections and then checking the URL. Like kayak.com, trainline.com also proposes the “best” option, However, by comparing the proposed “best” travel with the other proposed travels for some OD-pair connections, it was found that this “best” option does often not seem the best. Therefore, the ticket price and travel cost of the first 8 proposed connections are extracted (see Appendix C). If the website shows less than 8 connections, the script commands to additionally load later connections. Then, the generalised costs are calculated for these 8 connections (resp. less, if less than 8 connections could be loaded) as follows:

$$G = TT \cdot VTT + TC + N_{transfers} \cdot Penalty_{transfers}$$

Equation 22: Generalised cost web scraping rail

Where:

G	Generalised costs for an OD-pair connection
TT	Travel time
TC	Travel cost (ticket price)
$N_{transfers}$	Number of transfers
$Penalty_{transfers}$	Penalty per transfer

VTT is assumed to be 12 €. Even though transfer time is included in the travel time, a penalty is added for each transfer since each additional transfer decreases comfort and increases the risk of missing the next train. The penalty of an additional transfer is assumed to bear the same generalised costs as a ticket price increase of 12€ or an additional travel time of one hour. Therefore, the penalty has a weight of 12 in Equation 22. Finally, the connection with the lowest generalised cost is chosen.

After all, there are 11,161 OD-pair connections for which flight ticket data and 4,073 OD-pair connections for which train ticket data can be obtained. Taking the intersecting set of OD-pair connections with both data available and travel demand data available finally results in 2,998 OD-pair connections between 73 cities. Figure 18 shows the number of connections for each city for which travel cost and travel time for all three modes as well as demand data could be made available. In the following, a data analysis is undertaken for these OD-pair connections.

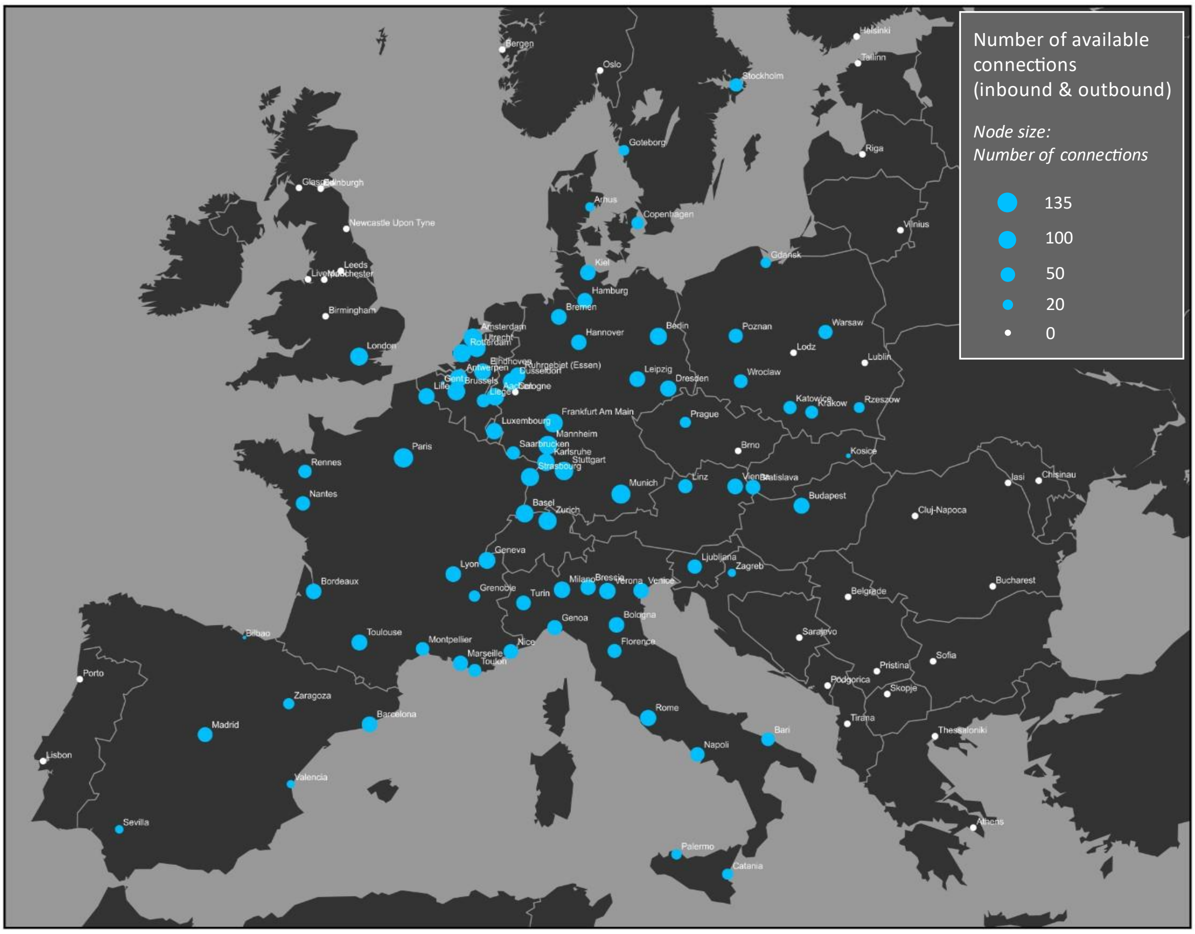


Figure 18: Number of connections (inbound + outbound) per city with available data

4.5. Data Analysis

In the following, the gathered data are analysed. Travel time and cost components as well as access/egress distance and detour factors for travel distance are already included, according to 3.4 Mode Specification.

4.5.1. Travel Distance

Figure 19 shows the distribution of travel distance of the OD-pair connections for all modes. It can be seen that air distance is usually shorter than rail and car distance. Therefore, emissions per air trip will be slightly lower than expected according to the emissions per passenger-kilometre, compared to emissions from rail and car trips.

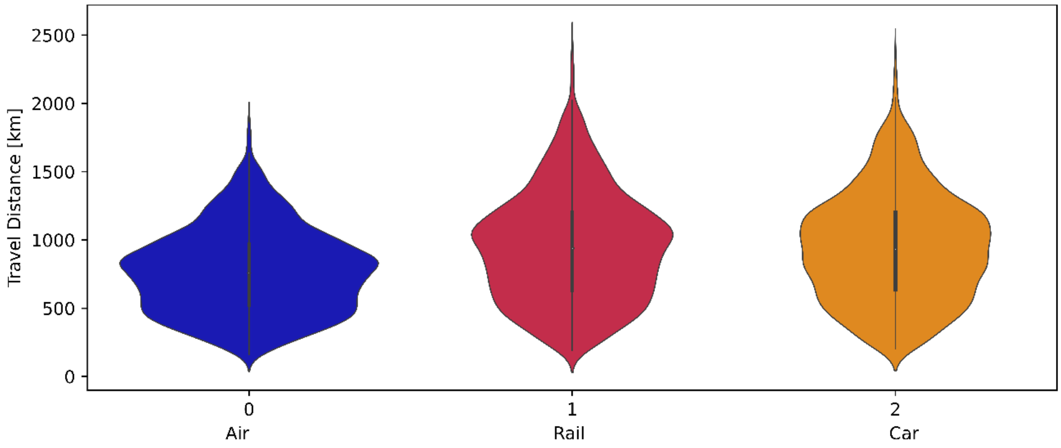


Figure 19: Violin plots of travel distance for air, rail and car (including air access and egress distance city to/from airport)

4.5.2. Travel Time

Figure 20 shows the distribution of travel time for air, rail and car. Figure 21 shows the travel time of each OD-pair connection and each mode depending on the direct distance. Therein, each blue dot is the air modal share of an OD-pair connection, each red dot the rail modal share of an OD-pair connection and each orange dot the car modal share of an OD-pair connection. It can be observed that air travel time distribution is much less flat (standard deviation of 143 min) than rail and car travel time distribution (standard deviation of 343 and 226 min). This can be explained by the fact that for air, longer distances increase travel time only slightly, because access, waiting and egress time hold a large share of total travel time. Many OD-pair connections have an air travel time of well four hours. These represent direct flights. Air travel times longer than 6 or 7 hours are from flights with a transfer. The median value is 334 min, and the average value is 381 min. Some OD-pair connections have very long rail travel times because several transfers are required and the waiting time in between legs can be long. Hence, rail tends to have longer travel times (median of 637 and average of 707 min) than car (median of 532 and average of 544 min).

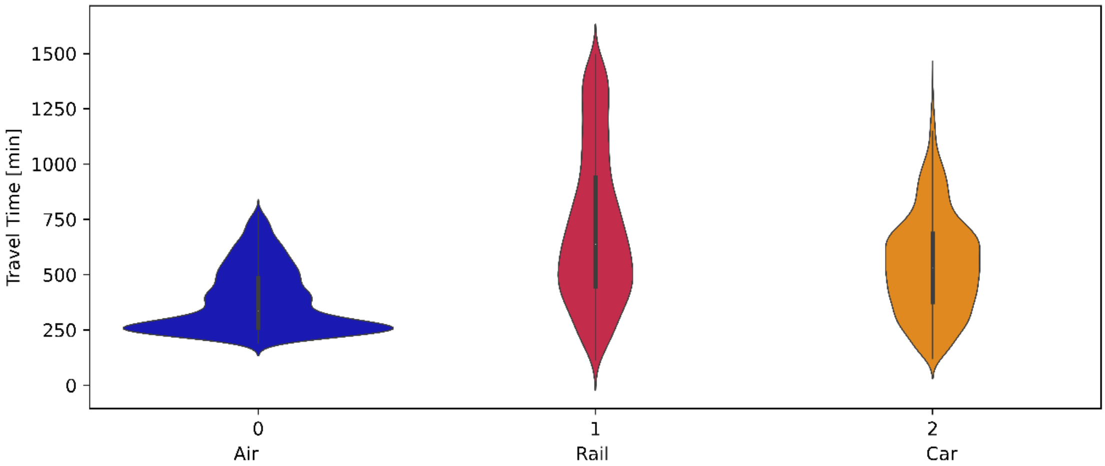


Figure 20: Violin plots of travel time for air, rail and car (including access, waiting, in-vehicle and egress time)

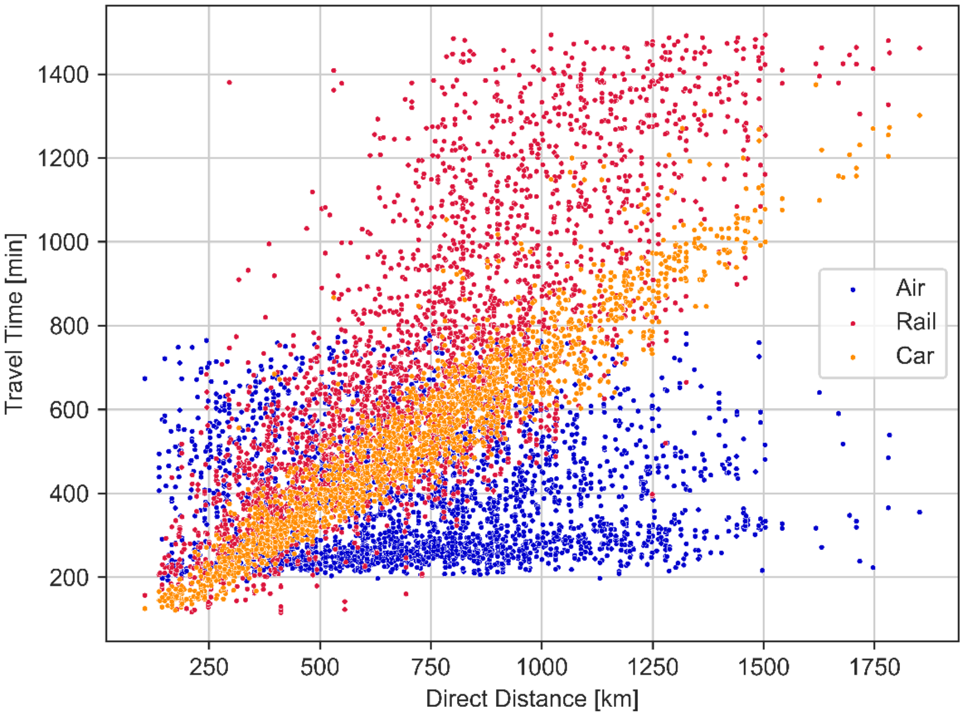


Figure 21: Travel time depending on direct distance for air, rail and car

4.5.3. Travel Cost

Figure 22 shows the distribution of travel costs for air, rail and car. Figure 23 shows the travel cost of each OD-pair connection and each mode depending on the direct distance. It can be observed that the distribution of air and rail travel costs is relatively similar. However, rail travel costs are lower (median value of 81€ and average value of 94€) than air travel costs (median value of 111€ and average value of 119€). Rail travel costs show a stronger correlation with distance than air travel costs. Car travel cost is proportional to distance, the median value is 91€ and the average value is 92€. Overall, travel costs differ much less between the three modes than travel times do.

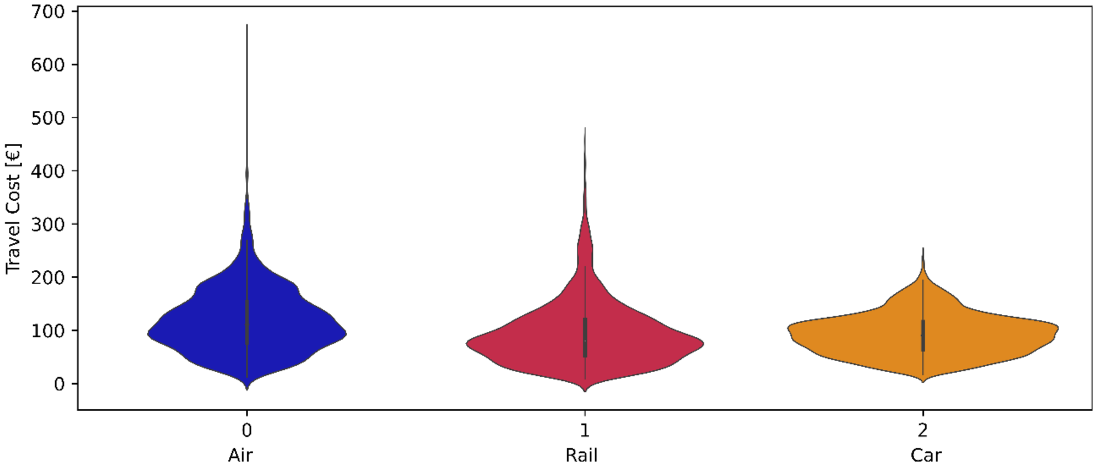


Figure 22: Violin plots of travel cost for air, rail and car

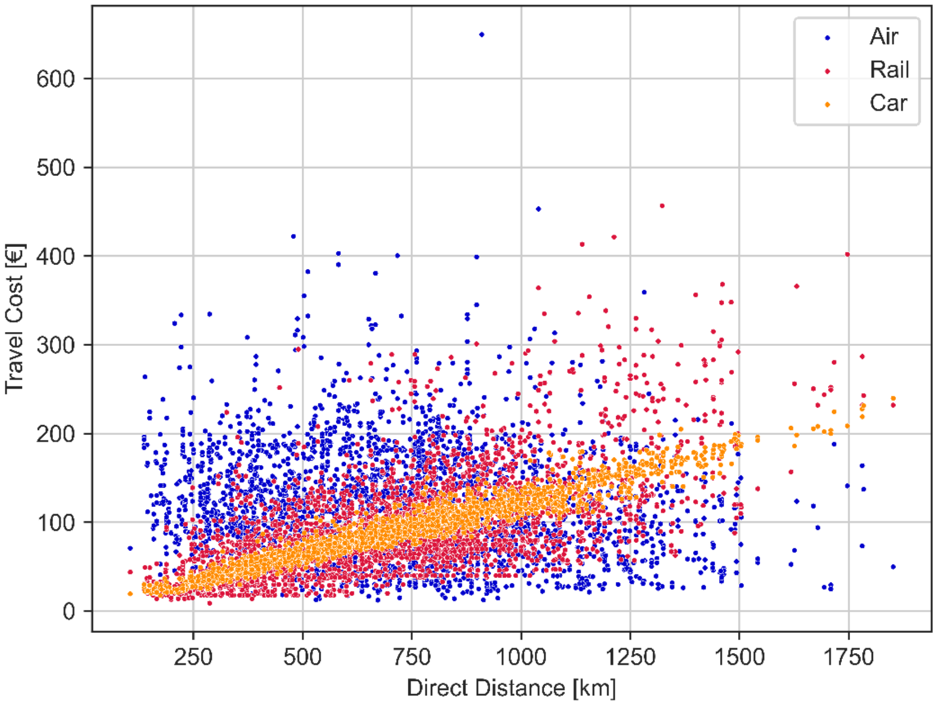


Figure 23: Travel cost depending on direct distance for air, rail and car

Besides distance, car travel costs depend on the fuel cost of the origin and destination countries (toll cost and vehicle occupancy are the same for each OD-pair connection (see section 3.4). Figure 25 shows a choropleth map of the fuel price depending on the country. It is apparent that the fuel price correlates with the prosperity of the country. Hence, the incorporation of a country-dependent fuel price can be regarded as reasonable, since air and especially rail tickets are usually also cheaper in less wealthy countries – which is as well considered in this study. If only an average fuel cost was taken, the modal share for car could be overestimated for wealthier countries and underestimated for less wealthy countries.

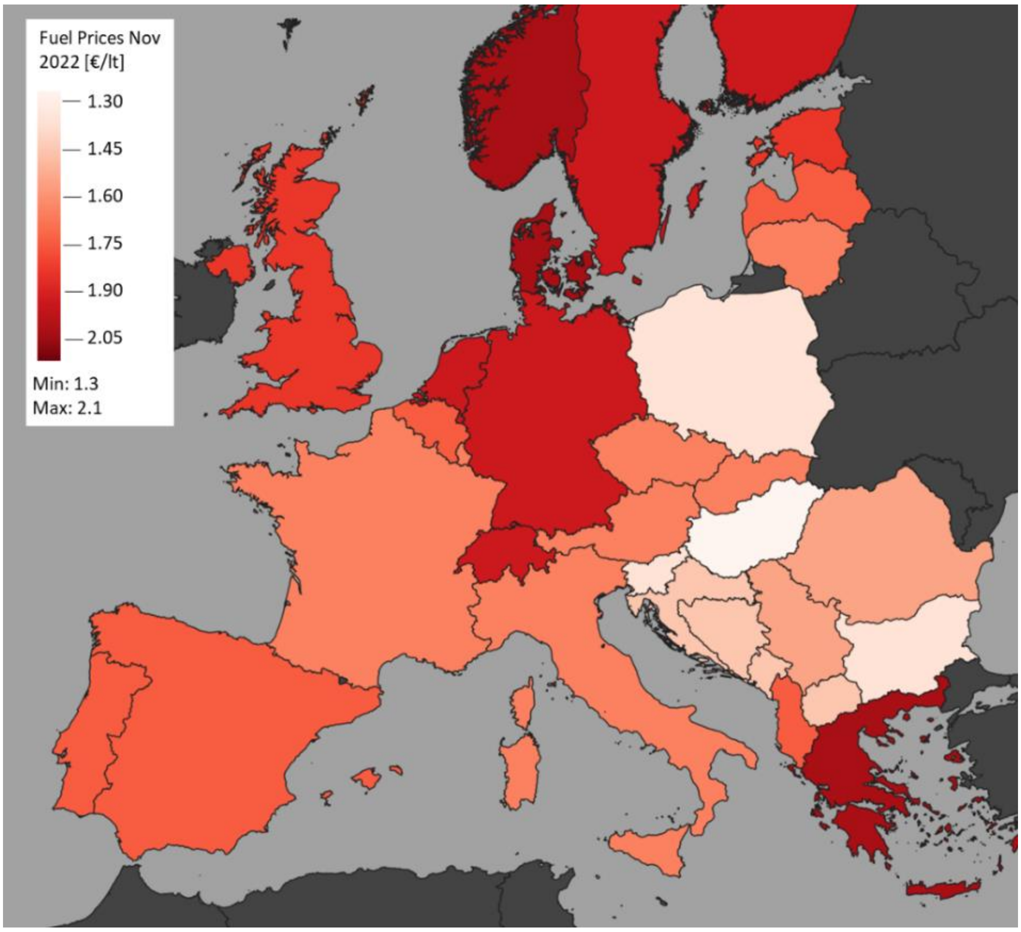


Figure 24: Fuel Price (November 2022) depending on the country

4.5.4. Value of Travel Time

The methodology of determining the VTT (see section 3.7) is applied to all countries within the perimeter. Figure 25 shows a choropleth map of the VTT. There are large differences between countries. Eastern European countries have the lowest values down to 1.5 € per hour. Switzerland, Luxembourg and Norway hold the highest values with almost 40 € per hour. Figure 26 exemplarily shows the VTT for trips starting or ending in the Netherlands depending on the origin and destination country.

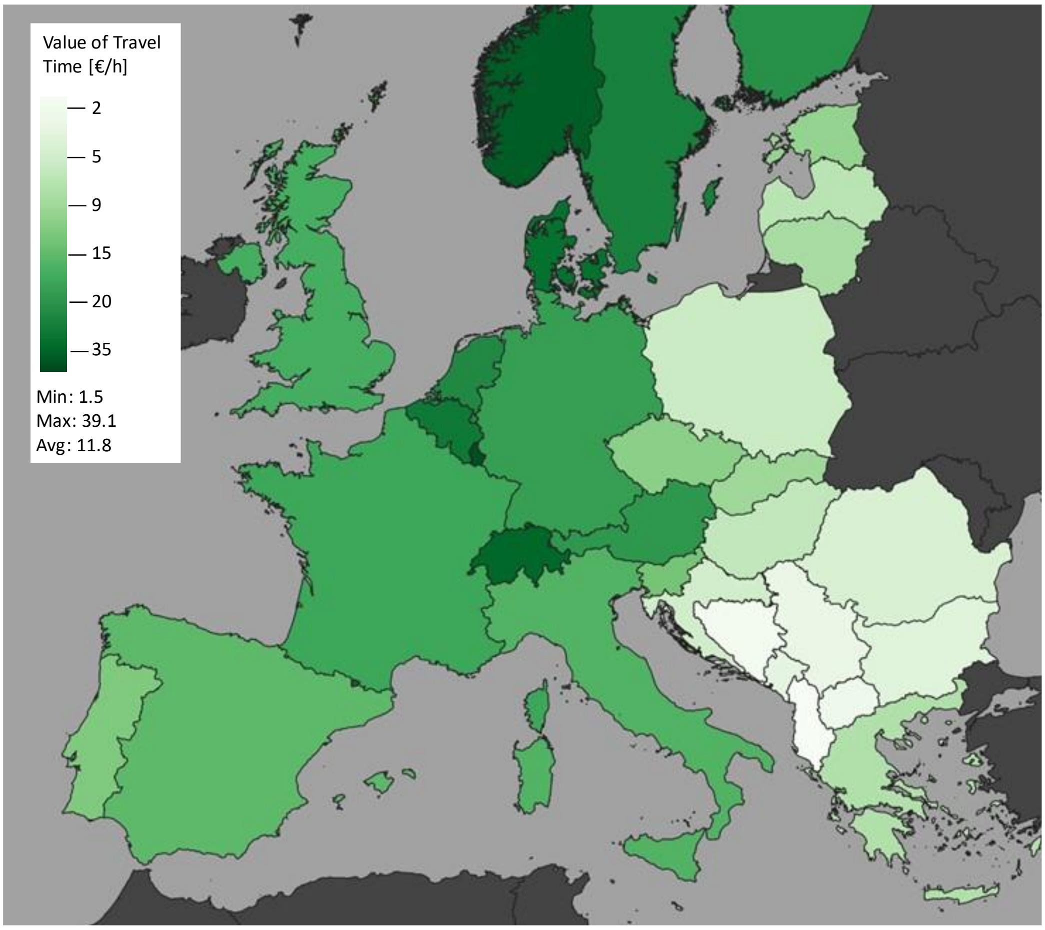


Figure 25: VTT depending on the country

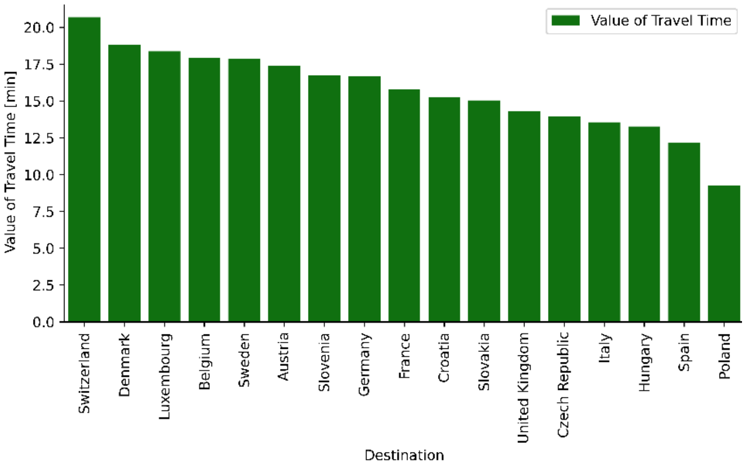


Figure 26: VTT to/from different countries for trips starting or ending in the Netherlands

4.5.5. Credit Expenditure

In the literature review (section 2.3.4) the correlation between long-distance travel and income was explored and in section 3.10.1 it was decided to use income elasticity of demand to derive the credit expenditure per person for each country. Christensen and Nielsen (2017) investigated the people's frequency of long-distance travelling in different countries. Computing the correlation with the individual credit expenditure depending on the country shows that using an income elasticity of 1.4 (see section 3.10.1) can be regarded as reasonable. The correlation between credit expenditure and journeys (“outbound 4+ nights”) per inhabitant is 83.9%, which indicates a strong positive correlation. The correlation is computed based on 28 countries which are within the perimeter.

4.5.6. Credit Need

Section 3.10 explained the methodology of deriving the credit expenditure from income and of calculating the credit need (per citizen of each country) from credit expenditure and credit allocation. Figure 27 shows the credit need per citizen in % of the allocated credits depending on the origin country. This is the credit need in today’s situation without TMC. For example, the Netherlands holds a credit need of 150%, which means that a Dutch citizen’s credit expenditure is 150% times higher than the free allocated credits. The maximum value holds Switzerland where a citizen would need to additionally buy 328% of the allocated credits to fulfil his or her travel desires. The minimum values hold the Eastern European where people would sell up to 75% of their credits. Note that this is the theoretical credit need if credits were for free (resp. there is no TMC). Due to the credit costs, the credit need will decrease because people are incentivised to use more rail instead of air and car and to cancel trips.

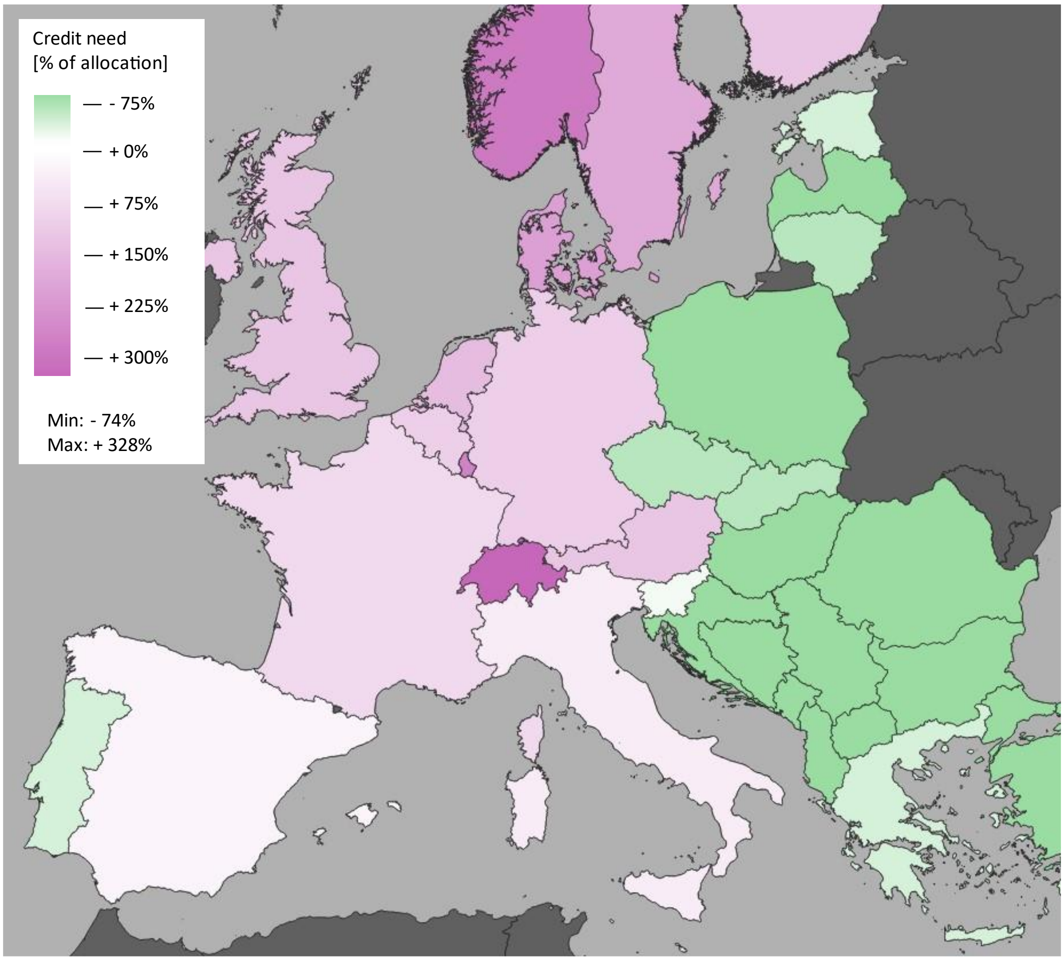


Figure 27: Credit need per user depending on the country [% of allocated credits]

V. Results & Discussion

This chapter presents the results of the case study (chapter IV) applying the methodology described in chapter III. In the first section, an overall perspective of the results is provided. Therein, the impacts of the TMC on the complete set of OD-pair connections are provided and the emerging market situation is illustrated. The section starts with an overview of the average modal shares and emission shares. Then findings about the credit price are provided, followed by the costs for travellers induced by the TMC, and the demand change due to the TMC (trip cancellation rate). Then, insights into the modal shares and the modal shift induced by the TMC depending on travel distance are provided. In the second section, a focus perspective is provided. The impacts of the TMC on the modal split as well as further impacts are presented for a selected set of routes. In the third section, results are analysed from an OD-pair connection characteristics perspective. Therein, OD-pair connections are categorised according to how they are affected by the TMC. The categorisation is undertaken by modal share, emission reduction and trip cancellation rate. For all results, unless otherwise stated, the emission reduction target is set to 30% as chosen in section 4.2. In the following, the terms "long-distance", "medium-distance" and "short-distance" refer to the length of the distance compared to other routes of this case study, and not to the terms commonly used in the transport sector.

Notice that modal shift can be expressed as an absolute value or a relative value. The absolute value is the difference between the modal share under TMC and the initial modal share. It is in the following called *Modal shift*. The relative value is the difference between the modal share under TMC and the initial modal share divided by the initial modal share. It is in the following called *Relative change of modal share*. For instance, if the initial modal share is 30% and the modal share under TMC is 60%, the modal shift would be +30% and the relative change of the modal share would be +100%. Depending on the context, the modal share under TMC either includes or excludes the share of cancelled trips. If they include cancelled trips, air, rail and car share plus the share of cancelled trips add up to 100%. If they do not include cancelled trips, only the trips that are indeed undertaken are focused on which means that the shares of air, rail and car add up to 100%. If not otherwise stated, the cancelled trips are excluded.

5.1. Overall Perspective

Figure 28 shows the average modal share (from all OD-pair connections, weighted with passenger volume) and its change from the initial situation to the situation with TMC. The left graph shows it under the assumption of inelastic demand (excluding trip cancellation), and the right graph under the assumption of elastic demand (trip cancellation incorporated). Without TMC, exactly half of the trips are undertaken by air. It holds a share of 50.0%, while rail holds 22.8% and car 27.2%. Under TMC and the assumption of inelastic demand, the share of air halves to 25.7%, the share of rail more than doubles to 50.4% and the share of car slightly decreases to 23.9%. Under TMC, considering demand elasticity, the share of air still strongly decreases, but less, to 31.9%. The share of rail increases to 26.3%, which is still remarkable, but which is a small increase compared to the case of inelastic demand. This increase in rail share increases the passenger volume on rail – even though total travel demand is reduced. The share of car slightly decreases, to 24.8%. The share of cancelled trips is 17.1%. These travellers cancelling the trips would decide to not do the trip because of the cost increase they experience due to the TMC. Only considering the remaining trips, the share of air is 38%, the share of rail 32% and the share of car 30%. It is reasonable that the modal shift is higher for the case of inelastic demand since the emission reduction of 30% must be achieved by modal shift only. In the case of elastic demand, part of the emission reduction is achieved by the demand reduction, so modal shift contributes only partly to the emission reduction of 30%. The number of cancelled trips plus the number of air trips under TMC equals approximately the number of air trips without TMC. This is an indication that cancelled trips are mainly air trips. This hypothesis will be further investigated in section 5.1.3.

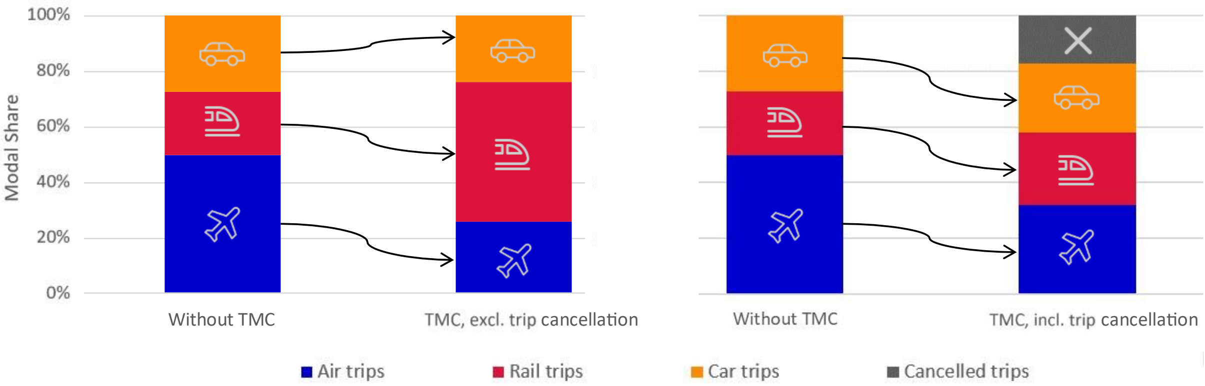


Figure 28: From initial modal share to modal share under TMC, excluding trip cancellation (left) and including trip cancellation (right)

Figure 29 shows the emission share (average of all OD-pair connections) and its change from the initial situation to the situation with TMC. The left graph shows it under the assumption of inelastic demand, and the right graph with incorporated elastic demand. Under TMC, due to modal shift (and trip cancellation for the case of elastic demand) part of the emissions are reduced. This part is indicated as avoided emissions.

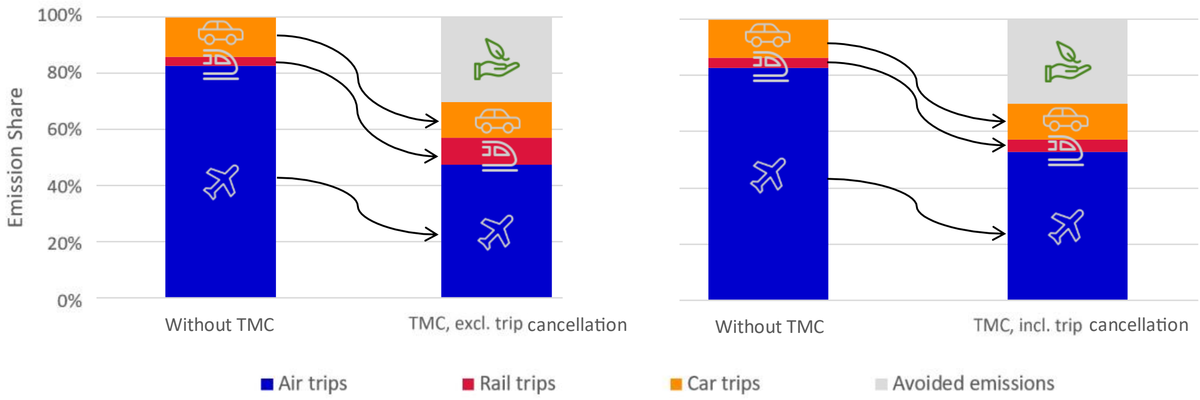


Figure 29: From initial emission share to emission share under TMC, with inelastic demand (left) and elastic demand (right)

In the initial situation without TMC, 83% of all emissions are from trips done by air, 3% from trips by rail and 14% from trips by car. As expected, the emissions are relatively high for air and relatively low for rail, compared to the modal share. Under TMC, 30% of emissions – which is the reduction target – are avoided, due to modal shift and trip cancellation. The TMC induces a reduction of the share of air emissions to 48% under inelastic demand and to 53% under elastic demand. The share of rail emissions increases to 9% under inelastic demand, which can be explained by the enormous increase in rail passengers resp. rail modal share. For elastic demand, it increases to 4%. The share of car emissions slightly decreases to 13% for both inelastic and elastic demand.

In the literature review (chapter II) it was identified that the long-distance emission share in Germany consists of 67% for rail, 25% for car and 4% for public transport (Reichert et al., 2016). Hence, the estimated initial rail value coincides well with the study’s public transport. The estimated initial air value is much higher, but the car value is lower. Since the set of OD-pairs consists of longer distances than expected within Germany and therefore of a higher air share, the estimated emission shares can be evaluated as plausible. The emission share of air can be validated by comparing it to the study by Christensen (2016). They found that air travel is responsible for 88% of Danes’ international travel which is a difference of 6% from the estimated value. Hence, the estimated air emission share seems reasonable. The study's higher value can be explained by that the study also includes intercontinental trips.

5.1.1. Credit Price

Executing the model for different emission reduction targets for both inelastic and elastic demand provides insights into credit prices emerging under different scenarios.

Figure 30 shows the equilibrium credit price depending on the target. The orange curve represents the results under the exclusion of trip cancellation (inelastic demand), and the dark red curve under the inclusion of trip cancellation (elastic demand). In both cases, the credit price increases approximately linearly with the emission reduction target of up to about 60%. For higher emission targets, the credit price starts to strongly increase. Under elastic demand, the credit price is 62€ per ton for an emission reduction target of 10%, 126€ for a target of 20%, 193€ for a target of 30%, 267€ for a target of 40% and 361€ for a target of 60%. For targets up to 50%, the credit price is approximately four times higher under inelastic demand.

For inelastic demand, the emission reduction target does not exceed 78%. This value can be achieved if the credit price is extraordinarily high, and a further increase in the credit price does not reduce emissions anymore. The reason for this is that in this condition – in which the emissions are 22% of the initial emissions – the modal share for rail is 100% for all OD-pair connections. Due to the inelasticity of demand, trip cancellation is never possible, and the reduction is caused by mode shift only. The value of 78% comes from the ratio of emissions of a trip by air and by rail, and the initial modal share (the potential of mode shift towards rail). If the case study included more OD-pair connections with a low initial modal share for rail, a higher reduction could be achieved. If emissions per passenger-kilometre for one mode would change, the value would change (for example higher if air emissions increase compared to rail emissions). Modelling demand as elastic results in a more reasonable outcome. Even an emission reduction target of 100% (zero emissions) would be possible. In that case, the credit price would head towards infinity, which would lead to cancelling of all trips.

The values obtained under elastic demand coincide well with values illustrated in the literature review in chapter II. OECD (2013) estimated effective carbon prices of 65 to 153€ per ton. Also, WTP for CO_2 emissions was found to be within this range (Alberini et al., 2018). The future cost of carbon capture and storage was estimated to be 100 to 200€ per ton. Hence, the credit costs under reduction targets of 10 to 30% match the studies' insights. Consequently, the chosen target of 30% and the therewith resulting cost per credit in the case of elastic demand can be evaluated as reasonable.

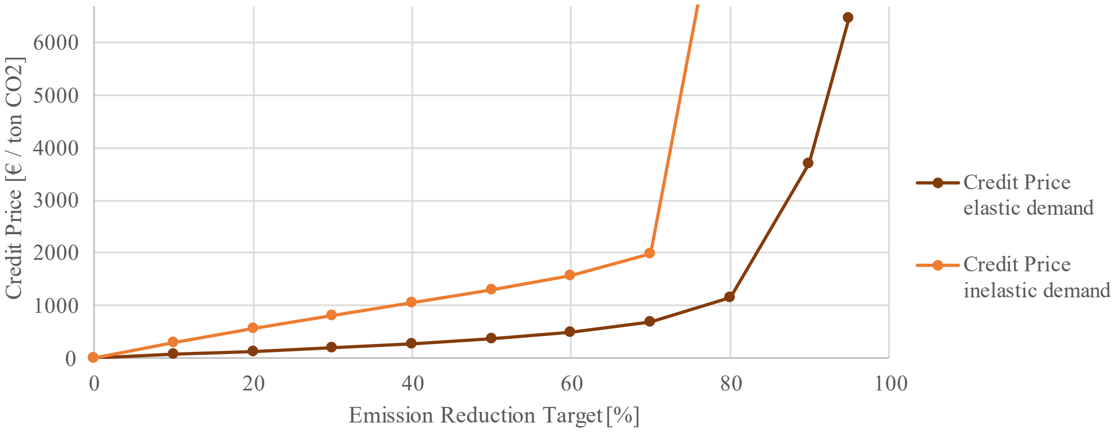


Figure 30: Credit Price depending on the emission reduction target

Figure 31 provides insights into the evolution of the credit price (left) and the emission change (right) during a model run. 20 iterations are executed for the case of elastic demand. The more iterations, the more the credit price and the emission change approach their equilibrium. After about 15 iterations the emission reduction target of 30% is achieved and the credit price stabilises at 193 € per ton of CO_2. Notice that the iterations only serve to approach the equilibrium and do not represent time. Hence, the resulting credit prices and emission changes before reaching the equilibrium do not happen in the market.

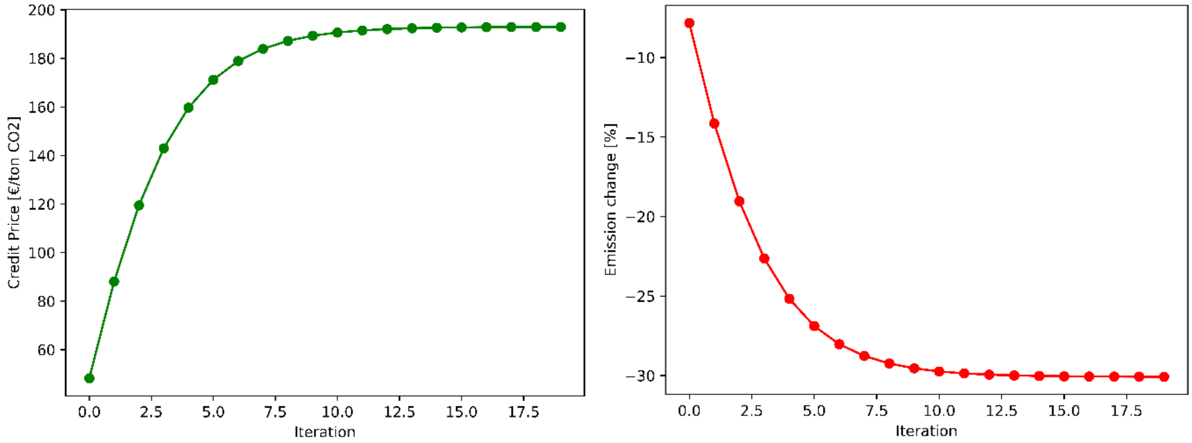


Figure 31: Evolution of the credit price (left) and the emission change (right) during 20 iterations (elastic demand, emission reduction target of 30%)

5.1.2. Credit Costs for Travellers

This section provides insights into the additional costs that travellers experience due to the TMC. These additional costs are credit costs, which depend on the CO_2 emissions of the trip. For trips where the credits allocated for free suffice and no additional credits need to be bought in the market, one could think that the credit cost is 0. However, the traveller could sell these credits if he or she did not travel. Therefore, he or she still experiences a credit cost when travelling because the potential earnings from selling the credits fall away. For this reason, it was decided to add up the credit costs to the travel costs for any case (see section 3.10.5). Figure 32 shows the distribution of credit costs for air, rail and car, incorporating all OD-pair connections. The graph is for the case of elastic demand and an emission reduction target of 30%, which holds a credit price of 193€ per ton of CO_2. The credit costs are 10 to 60€ for most air trips, 0 to 10€ for most rail trips and 5 to 40€ for most car trips. On average (weighted with passenger volume), they are 30€ for air, 5€ for rail and 18€ for car trips.

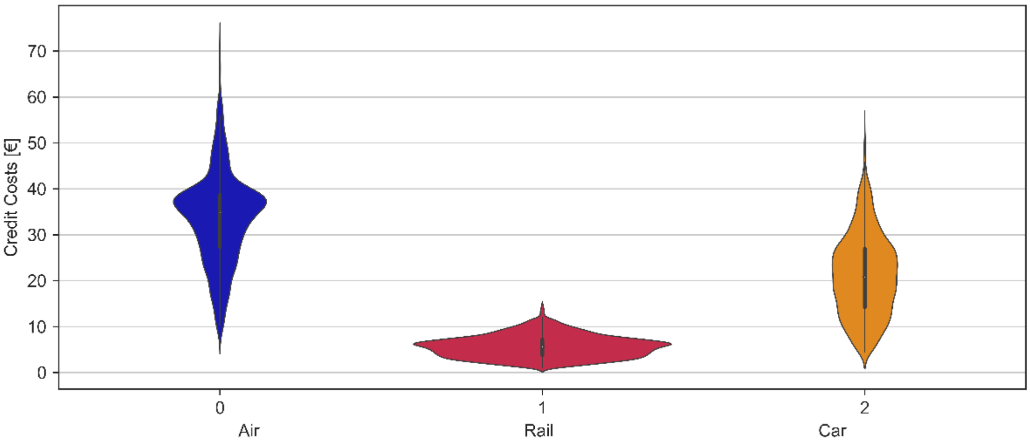


Figure 32: Violin plots of credit costs per air, rail and car trip (elastic demand, emission reduction target of 30%)

The maximum increase in air travel cost caused by the TMC is 307%. This is the case for a flight from Rome to Toulouse. As travel costs are only 13€, the costs for the credits are three times higher.

5.1.3. Trip Cancellation Rate

These additional costs lead to a reduction in demand. Therefore, trip cancellation (elastic demand) has been considered in the model by incorporating the price elasticity of demand (see section 3.10.6). It is found that the total demand reduction is 17.1% (reduction of passenger volume over all OD-pair connections and all three modes). The magnitude of demand reduction depends on the ratio of initial travel costs (without TMC) and credit costs. Figure 33 shows the trip cancellation rate for each OD-pair connection and each mode depending on the initial travel cost. Cancellation rates for rail trips are less than 5% on most OD-pair connections (nearly 90%). However, a few have a higher cancellation rate of up to 13%. They are slightly higher for trips with lower initial travel costs because for these the credit costs are relatively high compared to the initial travel costs. The cancellation rates for car trips are between 8 and 12% for all OD-pair connections. Since car travel costs as well as credit costs are proportional to travel distance, initial travel costs are proportional to the trip cancellation rate. The deviations within 8 and 12% are only caused by differences in fuel prices, which depend on the origin and destination of the OD-pair connection and therefore slightly affect the initial travel cost per passenger-kilometre. Cancellation rates for air trips strongly depend on initial travel costs. The lower the initial travel costs the higher the cancellation rate. Hence, high trip cancellation rates mainly happen for low-cost flights where credit costs are proportionally high while low trip cancellation rates for air occur when ticket prices are high. The latters are at the level of the cancellation rates of car or even rail trips.

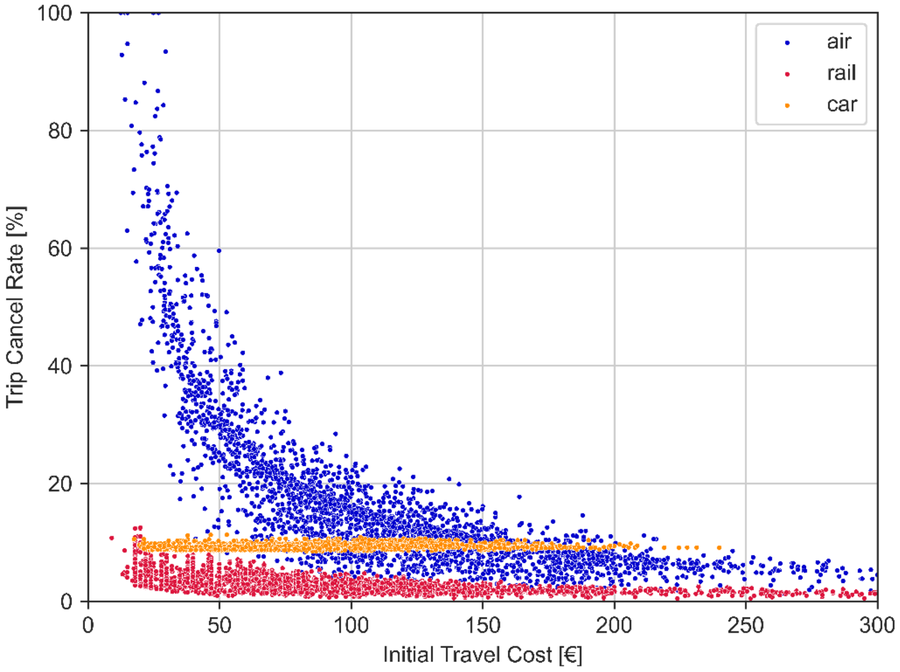


Figure 33: Trip cancellation rate for each OD-pair connection and each mode, depending on initial travel cos

Figure 34 shows the trip cancellation rate for air, rail and car depending on the emissions of the trip. For rail and car, it shows a similar picture as before in Figure 33. All rail trips hold low emissions and low cancellation rates. All car trips hold cancellation rates which are almost independent of the emissions of the trip. For air trips, there is a tendency that the higher the emissions the higher the cancellation rate. This is reasonable as trips with higher emissions have higher credit costs and therefore a higher chance that the share of credit costs from total travel costs is high.

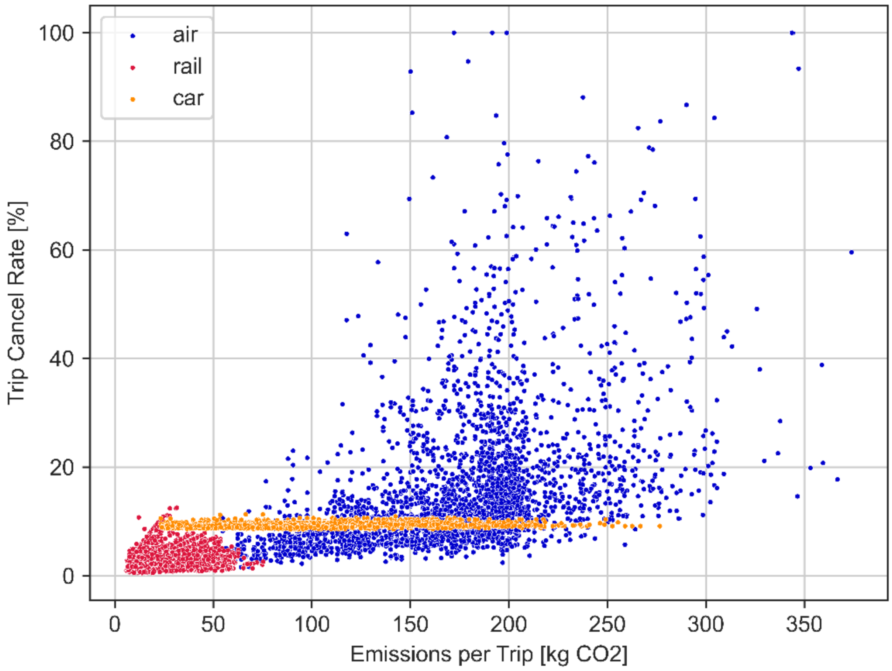


Figure 34: Trip cancellation rate for each OD-pair connection for air and rail, depending on emissions of the trip

5.1.4. Modal Shares & Modal Shift

Figure 35 shows the modal share depending on the direct distance. The graph above shows the initial situation without TMC, the middle graph the modal share under TMC assuming inelastic demand and the graph below the modal share under TMC incorporating elastic demand. Notice that the modal share under TMC and elastic demand does not include the cancelled trips, so air, rail and car share add up to 100%. One dot represents the modal share of one mode of one OD-pair connection, whereby blue dots stand for air, red dots for rail and orange dots for car. For instance, Zurich-Rome, which is a direct distance of 694km, holds an initial air share of 79%, a rail share of 10% and a car share of 11%. Therefore, in Figure 35 above there can be found a blue dot at y=79%, a red dot at y=10% and an orange dot at y=11%, all with an x-value of 694km. Due to the high number of data points (3 modes times 2,998 OD-pair connections equals 8,994 dots) and large deviations, it is difficult to observe a pattern. Hence, 3rd-degree polynomial functions (blue, red and orange continuous lines) that most closely fit the data are displayed (regression). The explanations below focus on these regression curves. Therewith, insights into the impact of the TMC on the modal split can be provided independently from particular OD-pair connections. Due to how the data on travel costs were collected (only one price per OD-pair connection and no price distribution), outliers and randomness in ticket prices can be avoided. The regression functions could also be used to estimate the modal share of a not yet considered OD-pair connection for which only direct distance is known, and travel cost and travel time are unknown. Notice that due to the regression, adding up the three polynomials does not for all distances equal precisely 100%.

The regression curves show that in the initial situation without TMC, rail and car are the predominant modes for OD-pair connections of distances below 500km. For these distances, car has a higher share than rail and the shorter the distance the larger the car share compared to rail. From 250km, air starts to become competitive, and its modal share begins to increase quite linearly. For OD-pair connections of 500km, the modal share of air and rail is equal. The break-even point of air and car share is 600km. For longer distances, air is the predominant mode, but up to 1,200 km, rail and car still hold a significant modal share. For distances above 1,200km, the share of air is nearly 100%.

These results can be compared with insights from Figure 6 in chapter II, where Donners (2016) also shows the modal share depending on the distance. The curve of the air modal share is comparable, yet this thesis finds a lower air share than Donners (2016) did – 25% vs. 40% air share at 500km and 60% vs. 75% air share at 800km. The shape of the rail and car share curves are slightly similar, but hold differences: First, Donners (2016) found a much higher rail share and a much lower car share. Second, he estimated an increase in rail share with increasing distance up to 300km. The presented study estimates a continuous decrease with increasing distance. However, both results would be quite alike if rail and car shares were merged and opposed to the air share. Since rail and car often have comparable travel times, they could be seen as one competitor to air. On the one hand, if more variables were included in the mode choice model, a comparable modal split as Donners (2016) estimated could have been obtained. For instance, by incorporating car ownership, and not just assuming that everyone has a car available, a large part of the car modal share could have been expected to shift to rail, and the curves would have looked alike. On the other hand, this study only incorporates fuel and toll costs for car travel costs. If the complete lifecycle costs of the car were considered, car travel costs would be much higher.

Rail benefits from having the least CO_2 emissions per passenger-kilometre. Therefore, a trip by rail has lower credit costs than the same trip by air or car and becomes more competitive when credit costs are included. Looking at the modal split under TMC and inelastic demand (middle graph) shows that this is the case for all distances. The increase in rail share happens mainly at the cost of air, but also at the cost of car. Only for less than 300km car holds a larger share than rail. From 300km to 1,050km, rail is the predominant mode with well 50% modal share. The modal share of car is 60% for the shortest distances (vs. 75% in the initial situation). In contrast to the initial situation, it decreases continuously and stronger with increasing distance. Air travel starts to become competitive at 400km (instead of 250km in the initial situation). The air share equals the car share at 750km and the rail share at well 1,000km.

The curves emerging under TMC and elastic demand (lower graph) are a mixture of the first two situations. There is an increase in the rail modal share compared to the initial share, but to a much smaller extent than under the assumption of inelastic demand. Like in the initial situation, air starts to become competitive at 250km, but the increase of the air share with the increase of distance is slighter. At 600km (compared to 500km without TMC), air and rail share are equal. At 650km, air and car share are equal (600km in the initial situation). In contrast to the initial situation, rail is stronger than car for OD-pair connections of more than 900km.

Figure 36 shows the modal share depending on direct distance for air travel (graph above), rail travel (middle graph) and car travel (graph below). Each graph shows the modal share for the initial situation without TMC, the modal share under TMC with inelastic demand and the modal share under TMC with elastic demand. The data points are the same as in Figure 35, but the graphs are organised differently which helps to obtain further insights: modelling demand as inelastic leads to quite extreme modal shifts, especially for air and rail. Modelling demand as elastic dampens the shift. Since the price elasticity of demand leads to trip cancellation, only part of the emission reduction must be achieved by the modal shift, and the other part is achieved by the cancelled trips. The chosen value for price elasticity of demand (see section 3.10.6) determines the magnitude of damping – the higher the value the stronger the damping. A value of zero would correspond to no damping which would be inelastic demand).

Depending on distance, air modal share decreases by 20 to 30% under inelastic demand and by 5 to 10% under elastic demand. For rail and car, the distance influences the modal shift caused by the TMC much more. The impact on the rail modal share is largest for medium-long distances, where the modal share increases by up to well 40% (inelastic demand) and 10% (elastic demand). For inelastic demand, rail modal share becomes enormously high at distances around 600km (up to 60%). Car modal share decreases due to the TMC, but to a smaller extent than rail increases. The biggest car modal shift happens for shorter distances. It is up to a decrease of 20% for inelastic demand and almost 5% for elastic demand. For long distances (more than 1,000km under inelastic demand and more than 600km under elastic demand), the TMC does hardly affect the car modal share.

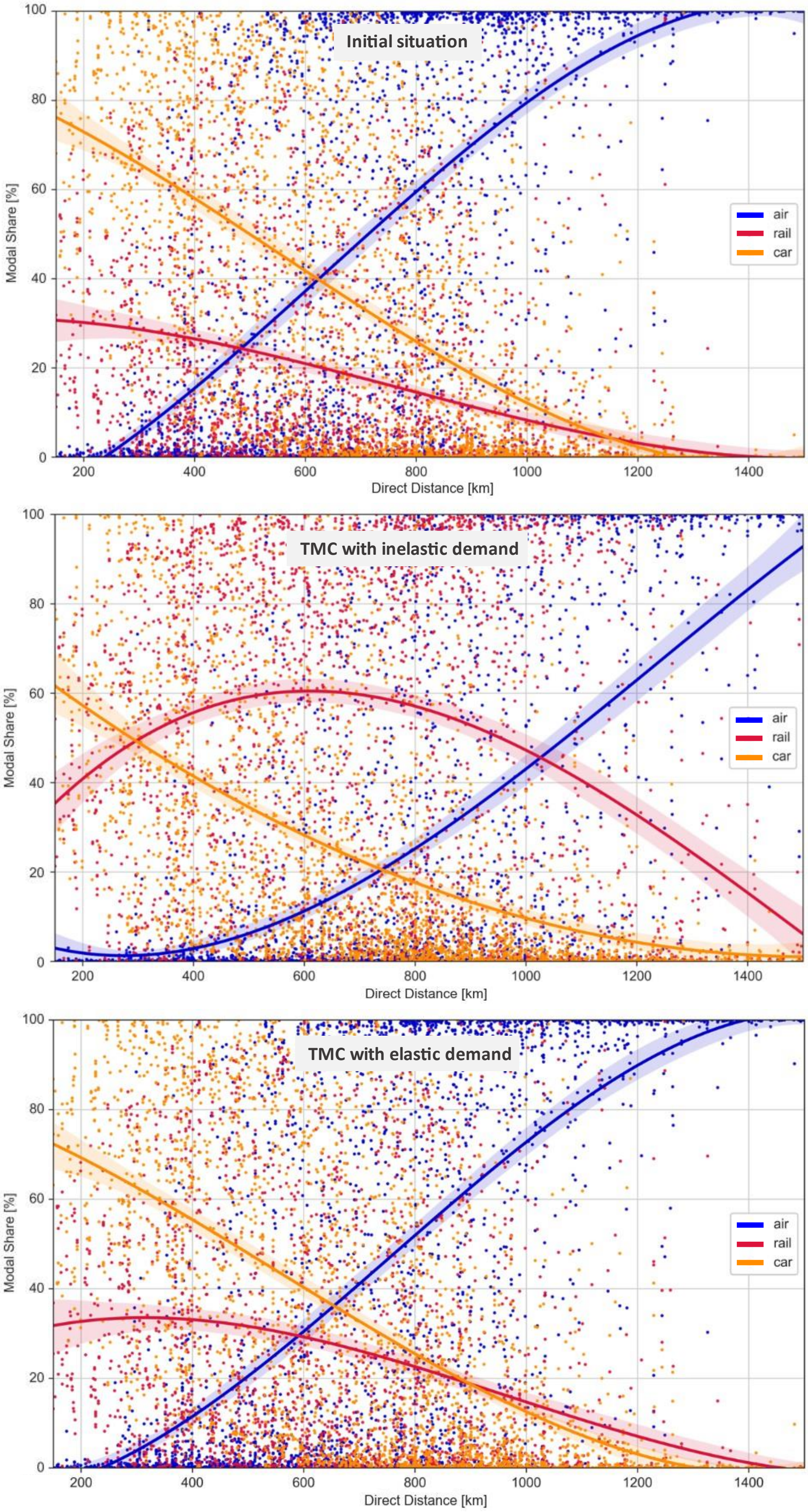


Figure 35: Modal share for each OD-pair connection and each mode, depending on direct distance, with regression of 3rd degree polynomial. Above: Initial situation. Middle: Situation under TMC, inelastic demand. Below: Situation under TMC, elastic demand.

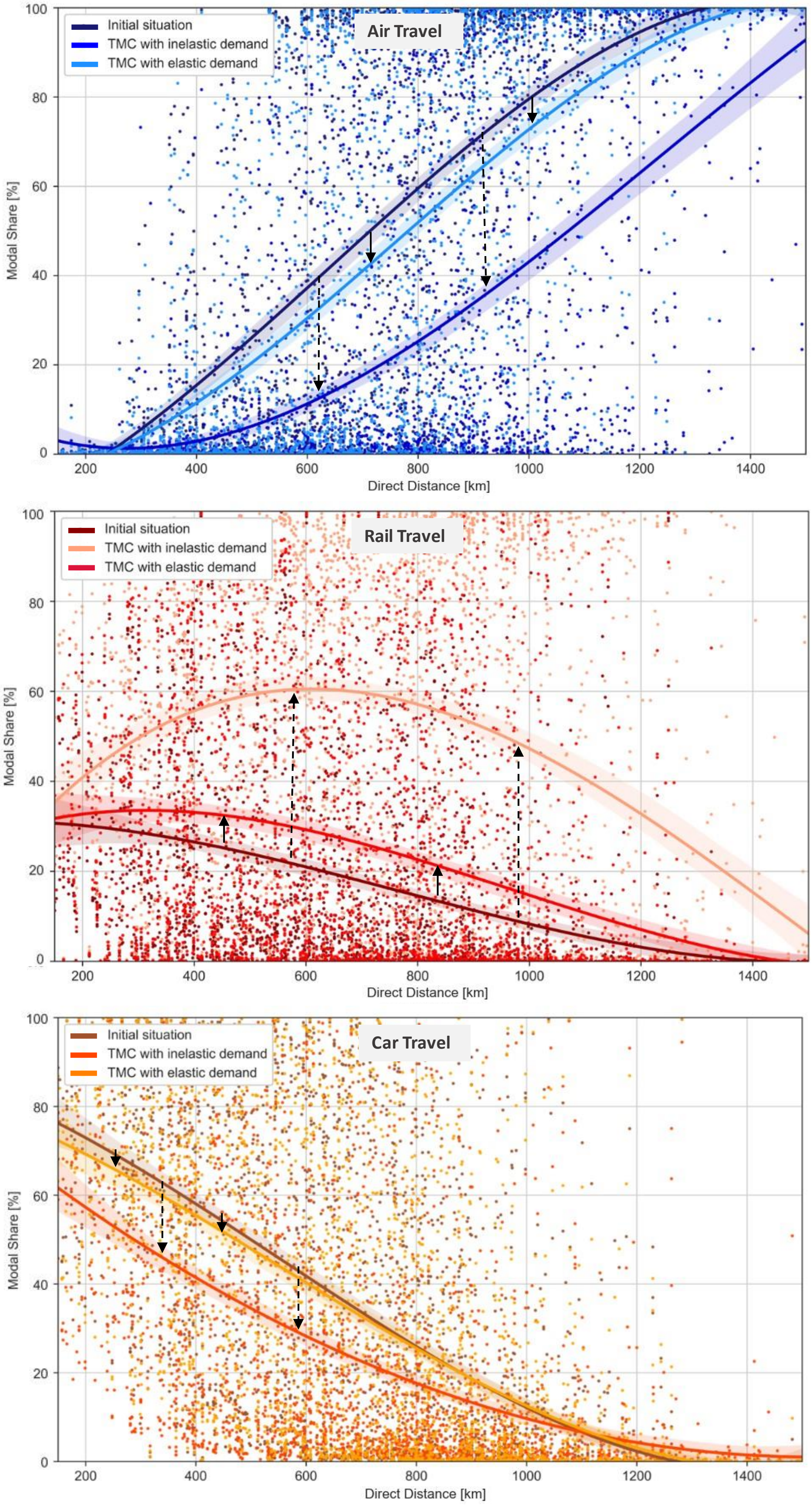
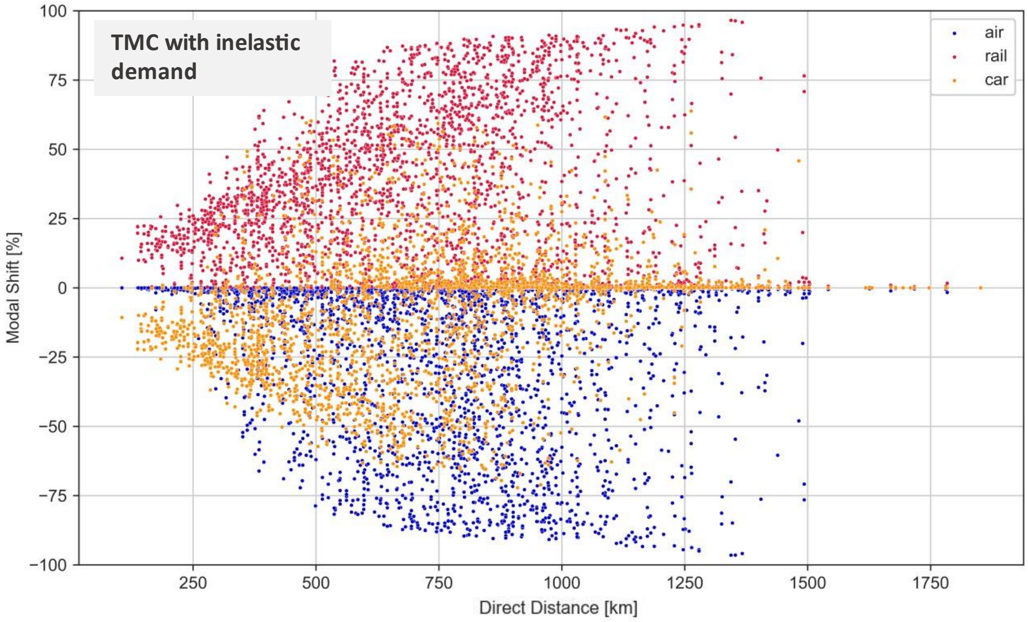


Figure 36: Modal share for each OD-pair connection and each case (initial situation, TMC with inelastic demand, TMC with elastic demand), depending on direct distance, with regression of 3rd degree polynomial. Above: Air travel. Middle: Rail travel. Below: Car travel.

Figure 37 shows the modal shift caused by TMC for each OD-pair connection and each mode, depending on direct distance (graph above for inelastic demand and graph below for elastic demand). These graphs represent the gap between the regression curves in Figure 36, but the distribution of the OD-pair connections' modal shifts is here better identifiable. Air modal shift is in all cases negative. For inelastic demand, values are widely spread from 0 to almost -100%. For elastic demand, the decrease of air modal share is not more than 30% for most OD-pair connections (for 99% of the OD-pair connections). Rail modal shift is in all cases positive. High rail modal shift mainly happens for medium and long distances (up to 100% for inelastic demand and up to 30% for elastic demand). Car modal shift is in some cases positive and in some negative. An increase of the car modal share happens on OD-pair connections where the TMC induces a larger shift from air to car than from car to rail (remember that car holds fewer emissions per passenger-kilometre than air, but more than rail). A negative car modal shift happens on OD-pair connections where the TMC induces a larger shift from car to rail than from air to car.

The TMC has the largest impact on the modal shift of all three modes for medium-long OD-pair connections from about 300 to 1,300km. On shorter OD-pair connections the modal shift is relatively low. A first reason for this is that the air modal share is already low on such OD-pair connections so a high modal shift away from air is not possible. A second reason is that rail is not a strong competitor for car since access and egress time hold a large share of total rail travel time. A third reason is that rail ticket costs are proportionally high compared to initial car travel costs and credit costs for car trips because initial car travel costs and credit costs for car trips are proportional to travel distance, while rail ticket costs are most times more expensive for shorter distances, relative to distance travelled. The TMC does not significantly affect the modal split on OD-pair connections of very long distances (more than 1,500km). This can be explained by that on these OD-pair connections rail and car are not a feasible alternative to flying because travel times for rail and car are extremely high.

The so far presented results made clear that incorporating elastic demand leads to a more realistic outcome than holding demand at a fixed level. Firstly, the credit price under elastic demand well coincides with insights from other studies. Secondly, the model shifts under TMC with inelastic demand are too high that they could be reasonable. Thirdly, it is simply unrealistic – especially for leisure trips for which the mode choice model is built – that there is nobody who cancels the trip when travel costs increase. Therefore, the next sections focus on the results obtained under the incorporation of trip cancellation and leave out the case of inelastic demand.



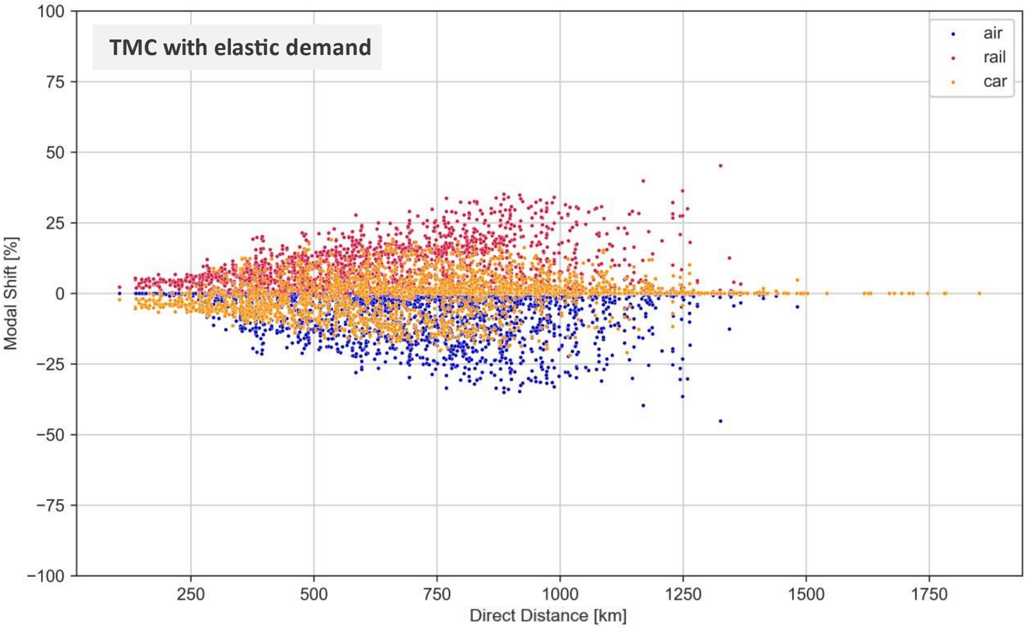


Figure 37: Modal shift caused by TMC for each OD-pair connection and each mode, depending on direct distance. Above: inelastic demand. Below: elastic demand.

5.2. Perspective of Focus Routes

From the overall perspective, findings about the equilibrium state of the credit market and about the impacts of the TMC on the traveller and the modal split (average and depending on distance) were explicated. This section provides insights into the impacts of the TMC on selected routes. First, the impacts on the modal split are explicated, followed by the impacts on emissions and travel costs.

As focus routes the following seven routes are chosen: *Amsterdam-Zurich*, *Amsterdam-Paris*, *Amsterdam-Berlin*, *Amsterdam-Vienna*, *Paris-Zurich*, *Paris-Madrid* and *Berlin-Vienna (all in both travel directions)*. On the one hand, these routes are selected because they originate and destine in cities which are large (more than one million inhabitants including the whole metropolitan area) and which are of high importance from a tourist perspective. Therefore, they generate a relatively large passenger volume of leisure travellers. On the other hand, these routes are chosen because they are distinct from each other regarding modal shares and modal shifts, and the cities are located differently (centrally in Europe vs. rather at the edge). Therefore, each route represents a certain type of route.

5.2.1. Modal Shares & Modal Shifts

Figure 38 shows a map of the focus routes and their modal share of air, rail and car. The map is displayed in a larger format in Appendix E. The bars show both the initial modal shares and the modal shares under TMC (width of bar proportional to modal share). For the initial modal share, air, rail and car share add up to 100%. For the modal shares under TMC, the white bars indicate the share of passenger that cancels the trip. Air, rail and car share plus the trip cancellation share add up to 100%. Figure 39 shows a ternary plot of the modal split for the focus routes. There, the modal shifts between air, rail and car induced by the TMC can be identified better. In contrast to Figure 38, the shares of air, rail and car under TMC add up to 100% (share from remaining demand). For both Figure 38 and Figure 39, the average values of both directions are taken. For instance, for Amsterdam-Berlin the initial air modal share is estimated at 68% for outbound and at 78% for inbound, so 73% is taken. The following explanations refer to Figure 38 as well as Figure 39.

On the *Paris-Madrid* route, air has a monopoly. Travel times of rail and car are too high and travel costs are not lower than for air. Hence, rail and car are not competitive. The TMC hardly induces a modal shift towards rail and car. Under TMC, the air modal share is estimated to be still above 99%. Since air travel costs increase by 61% by adding up the credit costs, every fourth trip is cancelled. This route has the highest trip cancellation share of all focus routes. For *Amsterdam-Vienna*, air is the predominant mode as well. Rail travel holds 1% and there is a considerable share of car travel of 8%. In contrast to *Paris-Madrid*, the TMC causes a significant increase of both rail and car shares to 4 and 13% (resp. 3 and 11% if trip cancellation share is included). On the *Paris-Zurich* route, with a share of 76% rail is the predominant mode in the initial situation. The TMC induces a further increase to 87% (resp. 83% if trip cancellation share is included). The reason for the low car share is that this route has a high level of rail service (direct TGV connection). The share of passengers cancelling the trip is only 4%, which is the lowest trip cancellation share of all focus routes. Credit costs are low as rail modal share is high, and rail emissions are relatively low. The *Amsterdam-Paris* route is comparable to the Zurich-Paris route, but car modal share is much higher at the cost of rail. Therefore, the TMC causes a higher trip cancellation share (8%) than for Zurich-Paris, as emissions and therefore credit costs of car travel are higher than for rail. The TMC causes a decrease in air modal share from 18 to 10% and a modal share increase for rail from 44 to 51%. With an increase from 38 to 39%, car share remains nearly the same. On the *Amsterdam-Zurich* route, air is predominant and also remains the most chosen mode with the introduction of the TMC. However, the TMC leads to more than a doubling of the rail share. It increases from 3 to 8%. Car modal share also increases, from 25 to 34%. On the *Amsterdam-Berlin* route, car is not very competitive because the cities are well connected by both air and rail. Air holds an initial modal share of 73% and rail of 44%. This route stands out with a large modal shift from air to rail, with a decrease of 25% for air and an increase of 22% for rail (resp. 32% and 17% if trip cancellation share is included). This can be explained by that flying is more attractive in the initial situation than rail travel, but since rail is also competitive already in the initial situation, it catches up a large part of travellers when TMC is introduced. The *Berlin-Vienna* route is mainly undertaken by car, which holds a modal share of 71%. Rail holds 25%, air is a niche with 5%. The TMC causes a shift from air and car to rail. The rail share increases to 36% (resp. to 33% trip cancellation share is included).

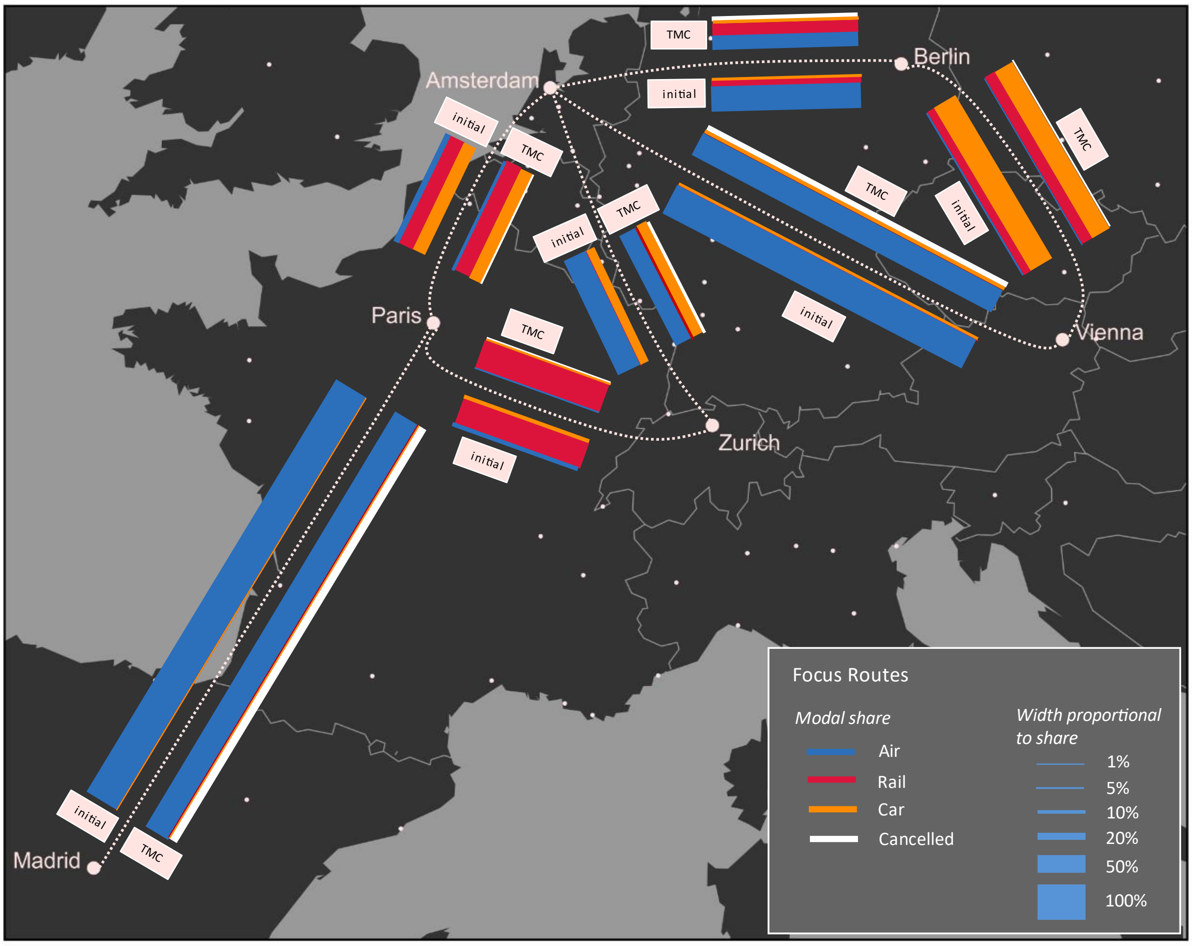


Figure 38: Modal shares and trip cancellation share of the focus routes – initial situation and situation under TMC

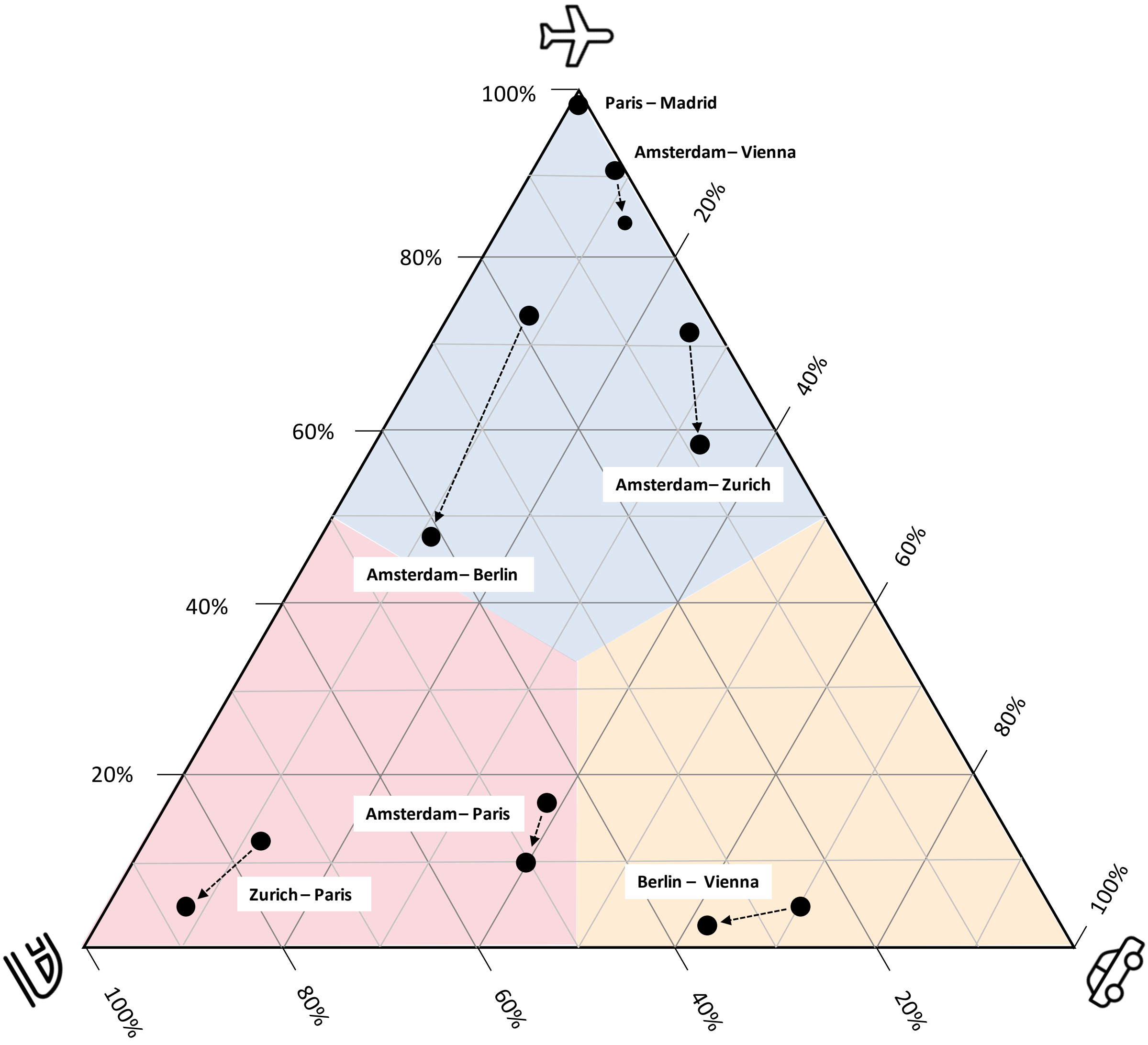


Figure 39: Ternary plot of the modal split for the focus routes – shift between air, rail and car induced by the TMC

To conclude, the TMC affects each route to a different extent. Shift always happens from modes with higher CO_2 emissions to modes with lower CO_2 emissions per passenger-kilometre. In Figure 39, the dots are "pulled", first mainly towards the bottom side of the triangle, and then towards the left bottom corner. For all routes, there is a shift away from air ("pull" towards the bottom side of the triangle). For most of the routes, there is a significant shift towards rail ("pull" toward the left bottom corner). As identified in section 5.1.4, the car modal shift can be positive ("pull" towards the right bottom corner) or negative ("pull" towards the right bottom corner). The first is the case for Amsterdam-Zurich, the latter for Berlin-Vienna. This is reasonable, since Berlin-Vienna holds a high initial car modal share, and the TMC incentivises the people to shift to rail. Amsterdam-Zurich on the contrary holds a high initial air share, which is reduced in favour of car and rail share. Furthermore, for routes where the shift away from air hardly happens (hardly "pull" towards the bottom side of the triangle), the share of passengers who cancel the trip can become high (Paris-Madrid or Amsterdam-Vienna). This is attributed to the credit costs which are high for air trips compared to the initial travel costs.

5.2.2. Emissions

Figure 40 provides an overview of the impacts of the TMC on the emissions of the focus routes. For each route, bars indicate the share of air, rail and car emissions from the total emissions of the route. In each case, the left bar represents the emission share in the initial situation without TMC, and the right bar stands for the emission share under TMC. For the latter, due to modal shift and trip cancellation, emissions are reduced. The reduced part is indicated as avoided emissions. For each route and both the situation with and without TMC, a green dot illustrates the average emissions per passenger-kilometre. The number below indicates the average percentual reduction of emissions per passenger-kilometre on the route.

The avoided emissions range from 17% (Amsterdam-Zurich) to 37% (Amsterdam-Berlin). Avoided emissions are not primarily achieved by shifting travellers from air to rail and car and from car to rail. They are to a large extent achieved by trip cancellation. Air trips are cancelled the most, car trips the second most and rail trips the least. Consequently, cancelled air trips most contribute to emission reduction. Due to the cancelled trips, the remaining modal share (excluding the share of avoided emissions) changes. For instance, assuming that demand for rail does not change, but many air travellers cancel their trip, the rail modal share will increase. Due to that fact emissions per passenger-kilometre decrease by a range from 0.4% (Paris-Madrid) to 30% (Paris-Zurich). Thereby, the shift of travellers from air to rail and car and from car to rail contributes to this decrease, but the main part is attained by a strong reduction in car and mainly air passenger volume. Low emission reductions per passenger-kilometre happen on the Amsterdam-Vienna route (4%) and the Paris-Madrid route (0.4%). These routes are characterised by a modal share of air which remains high. Hence, emission reduction per km stays nearly the same. High emission reductions per passenger-kilometre are the case for Amsterdam-Berlin (28%) and Paris-Zurich (30%). Here, rail modal share strongly increases due to the TMC. First, because a large part of air trips is cancelled. Second, because the absolute rail passenger volume increases at the cost of mainly air passenger volume.

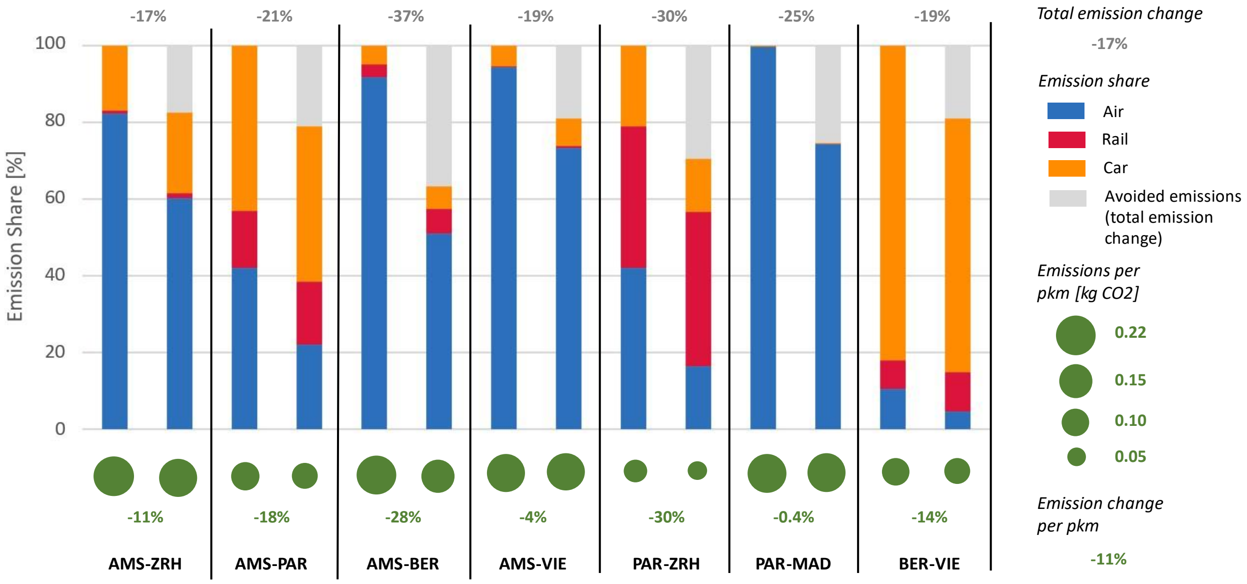


Figure 40: Emission share without TMC (left) and with TMC (right) for each focus route, total emission change, emissions and emission change per passenger-kilometre (pkm)

5.2.3. Travel Costs

Figure 41 provides insight into the impact of the TMC on travel costs. Each mode on each route is presented by a bar consisting of initial travel cost and credit cost. A traveller experiences the highest credit costs when flying between Paris and Madrid (41€ for one leg). For the same route, credit costs are 8€ when travelling by rail and 28€ when travelling by car. Notice that the ratio of these costs could be directly derived from the ratios of the emissions per passenger-kilometre and the ratio of the detour factors of the different modes. The highest percentual increase in travel costs due to the introduction of TMC is for flights between Amsterdam and Berlin and between Paris and Madrid (both +36%). For all routes, the percentual increase in travel costs when travelling by rail is between 5% (Amsterdam-Paris) and 10% (Amsterdam Berlin). This difference comes from differences in train ticket prices. The percentual increase in travel costs when travelling by car is around 18% for all routes (only small differences, due to fuel price variations).

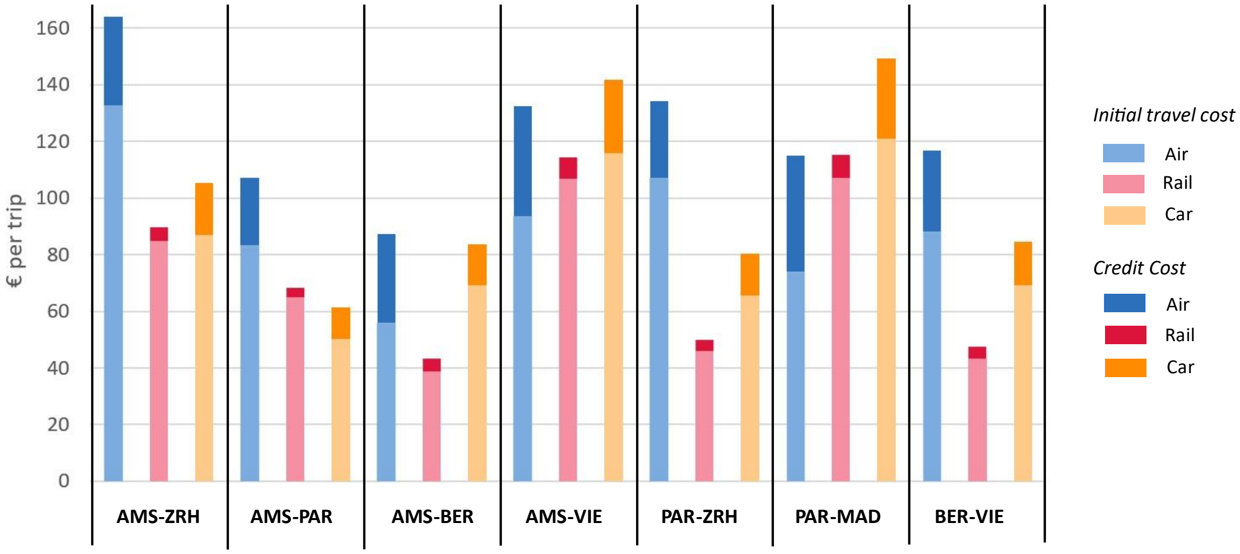


Figure 41: Initial travel cost and credit cost for air, rail and car on the focus routes

5.3. Perspective of OD-Pair Connection Characteristics

The section above provided insights into the impacts of the TMC on selected routes. The present section considers again all OD-pair connections and puts the perspective on their characteristics. Thereby, OD-pair connections are categorised. The first categorisation is done by modal share and modal shift, the second by emission reduction and the third by trip cancellation rate. Therewith, insights about how the TMC affects which types of OD-pair connections can be gained.

5.3.1. Modal Share and Modal Shift

Table 10 provides an overview of the categories created through filtering by modal share and modal shift. Notice that in the following the cancelled trips are not part of the modal split (air, rail and car share add up to 100%). For each category, the filter requirements and the number of OD-pair connections as well as the share from all OD-pair connections are provided. For each mode, there is one category of OD-pair connections with a high modal share and one category with a low modal share (initial situation as well as under TMC). For air and rail, there is a category with OD-pair connections holding a high modal shift. For car, there is one category with a high positive modal shift and one category with a high negative modal shift. The share of OD-pair connections where air modal share remains high under TMC is big. For 21% of all OD-pair connections, the modal share of air remains above 99%. Only 0.2% of all OD-pair connections have a higher modal share of rail than 99%. For car it is 1% of all OD-pair connections. Therefore, the threshold values for the categorisation are chosen differently.

Table 10: Categorisation of OD-pair connections by high modal shares, low modal shares and high modal shifts

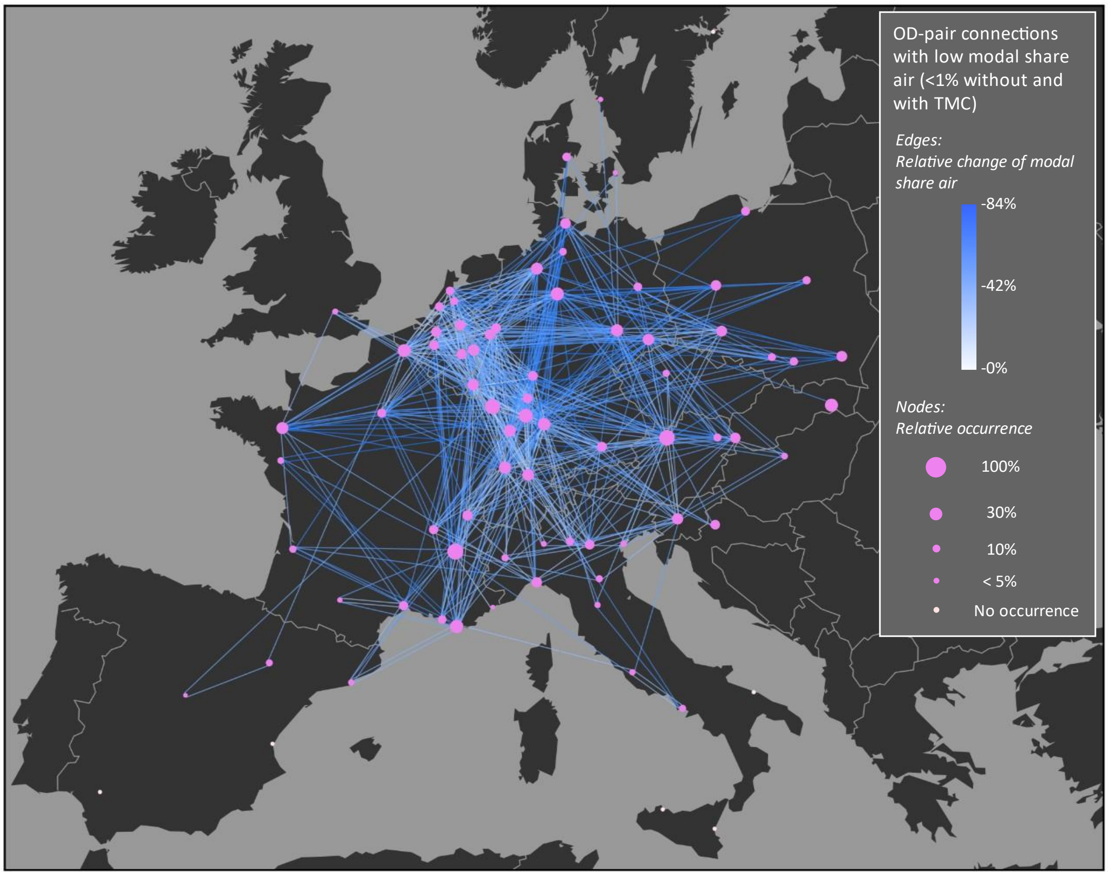
Categorisation	Initial situation		Situation under TMC		Number of OD-pair connections (share of all OD-pair connections)
By modal share air	low	< 1%	low	< 1%	634 (21 %)
	high	> 99%	high	> 99%	495 (17 %)
	no requirement		high shift	< -20%	193 (6 %)
By modal share rail	low	< 1%	low	< 1%	935 (31 %)
	high	> 50%	high	> 50%	374 (12 %)
	no requirement		high shift	> +20%	210 (7 %)
By modal share car	low	< 1%	low	< 1%	631 (21 %)
	high	> 80%	high	> 80%	401 (13 %)
	no requirement		high shift –	< -10%	268 (9 %)
	no requirement		high shift +	> +10%	128 (4 %)

In all maps of the present section, node size and colour represent the occurrence of connections in this category relative to the total number of connections to or from that city. The area of the dot (not the radius) is proportional to the relative occurrence. For instance, assuming a city has 100 connections in the dataset (sum of inbound and outbound) and 20% of these connections have an air modal share of less than 1%, then the relative occurrence of this city in the map is 20% and the dot size is adjusted accordingly. The relative occurrence is not an accurate indicator, especially for cities where only a few connections are included in the data. It should rather give an idea of whether a city is stronger or less strongly represented in a certain category. For routes which have two OD-pair connections (both directions), two edges are displayed. The edges are placed so that their direction is right-hand. In Appendix E all maps are again displayed in a larger format. Additionally, just for illustration, a map including all OD-pair connections is shown (second map of Appendix E).

First, OD-pair connections are categorised by modal share and modal shift of air. Figure 42 above shows the 21% of the OD-pair connections with a low air modal share (less than 1%). The colour of the edges represents the relative change of the air modal share. On these OD-pair connections, air travel is not competitive under TMC as well as without TMC. The air modal share is below 1% already without TMC. Therefore, the average air modal shift on the OD-pair connections within this category is only 0.2%. This category primarily includes OD-pair connections within central Europe. Cities in Spain, southern Italy, Sweden and the United Kingdom which are close to the edge of the perimeter are hardly represented. In contrast to the modal shift, the relative change of air modal share is -42.6% on average for all OD-pair connections within this category, which is almost a halving of the modal share. There are differences in the relative change of air modal share between the OD-pair connections (see dot sizes of the cities in Figure 42 above). A strong relative change of air modal share (up to 77%) primarily is the case for the rather longer OD-pair connections, for instance between cities in the Netherlands and Poland. The reason for this is that these OD-pair connections still have some potential to shift demand from air to rail or car. The OD-pair connections with the most moderate relative change of air modal share are characterised by short distances. Most of these OD-pair connections are between cities in the Netherlands, Belgium, Switzerland, the western part of Germany and the northern part of Italy. Here, there is hardly any potential to shift demand from air to rail and car because the initial air share is already much below 1%. This also explains the average trip cancellation rate of 7.4% within this category, which is half of the cancellation rate from all OD-pair connections.

On all OD-pair connections shown in Figure 42 above, rail travel shares the market with car travel. Due to the TMC, the average rail modal share increases from 40 to 45% at the cost of the car modal share (59 to 55%). A high modal shift from car to rail is mainly the case for OD-pair connections where rail already has a rather high initial modal share, for instance, Zurich-Hannover, where rail increases from 57% to 70%. Only a low modal shift from car to rail primarily happens on OD-pair connections where rail has either a low (nearly 0%) or a very high (nearly 100%) initial modal share. The first is for example the case for Turin-Strasbourg (rail share increases from 0.2% to 0.4%), and the latter is for example the case for Frankfurt-Kiel (share rail increases from 98.7 to 99.3%)

Figure 42 below shows the 17% of the OD-pair connections with a high air modal share (more than 99%). The colour of the edges represents the relative change of the rail modal share. On these OD-pair connections, air travel nearly has a monopoly and even remains a monopoly with the introduction of TMC, as the modal shift away from air is close to zero. Most OD-pair connections are characterised by a long travel distance. Mainly cities close to the edge of the perimeter have a high relative occurrence (for instance Madrid, Sevilla, Catania, Palermo). This can be explained by that they hold a larger share of longer distance OD-pair connections which decreases the competitiveness of rail and car. Even though the modal shift is small, all OD-pair connections have a relative increase in rail modal share of more than 200%. The highest relative increase of rail modal share is 1330%. The largest relative change of rail modal share happens on OD-pair connections where the initial air modal share is very high (around 99.9%) and therefore rail modal share is nearly zero. Hence, even if the absolute modal shift towards rail is small, passenger volume on rail easily increases by a factor of 10. This case is well represented for cities in Spain and southern Italy (for example Madrid-Berlin or Sevilla-Brussels). More moderate relative increases in rail modal share are on OD-pair connections where the initial air modal share is not that high (slightly above 99%). There, since already a bit a larger share of passengers initially travels by rail, the relative change of rail modal share is not that high (for example Venice-Prague or Antwerp-Milan). Furthermore, for some OD-pair connections there is only a moderate change in relative modal share because car travel is more attractive than rail, so demand shifts to car instead of rail. With 33%, the average trip cancellation rate is very high for OD-pair connections within this category. Every third trip is cancelled, which is due to the high air modal share and the air travel's high credit costs compared to initial travel costs.



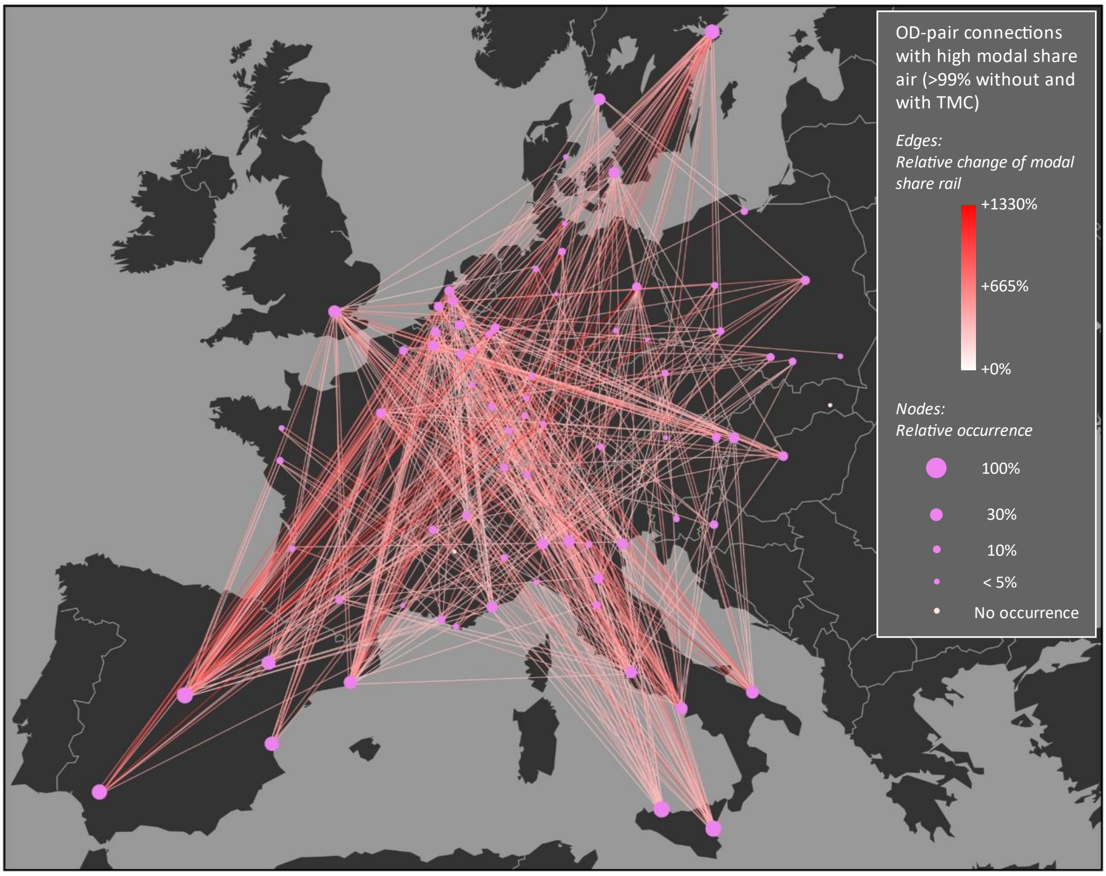


Figure 42: Above: OD-pair connections with ***low modal share air*** *(<1%). Below: OD-pair connections with* ***high modal share air*** *(>99%). Edge colour: Relative change of modal share air (above) resp. rail (below). Node size and colour: Relative occurrence per city.*

In Figure 43, OD-pair connections with a high air modal shift (more than a decrease of 20%) are illustrated, whereby the colour of the edges represents the air modal share under TMC. With a decrease of 45%, Kiel-Rome holds the highest air modal shift. However, 84% of the OD-pair connections within this category have a modal share decrease of between 20 and 30%. First, the OD-pair connections are characterised by medium travel distances. 80% are of distances between 500 and 1,000km (for all OD-pair connections included in the case study, 55% are within this distance range). Second, on these OD-pair connections, there is strong competition between the modes in the initial situation. On most OD-pair connections, air holds the highest initial modal share, but rail or car (or both), also have a proper modal share. Cities which have a high relative occurrence are mostly located in Poland, southern France, northern Germany and northern/middle Italy. These are cities which are neither at the edge nor in the centre of Europe and therefore have a lot of medium-distance OD-pair connections. Furthermore, eastern European cities have a high relative occurrence of OD-pair connections with a large decrease in air modal shift. This can be explained by that they are more cost- and less time-sensitive because they value time lower as their GDP per capita is lower (see VTT per country in Figure 25 in section 4.5.4).

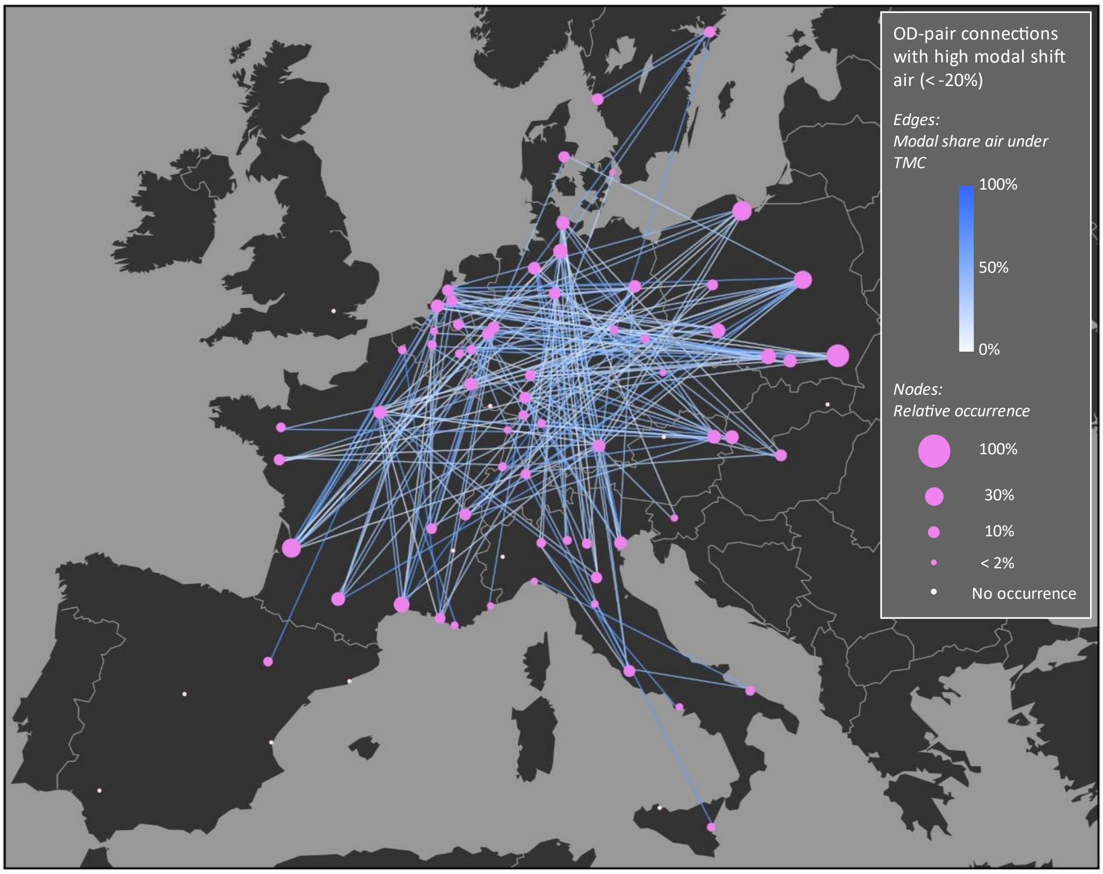
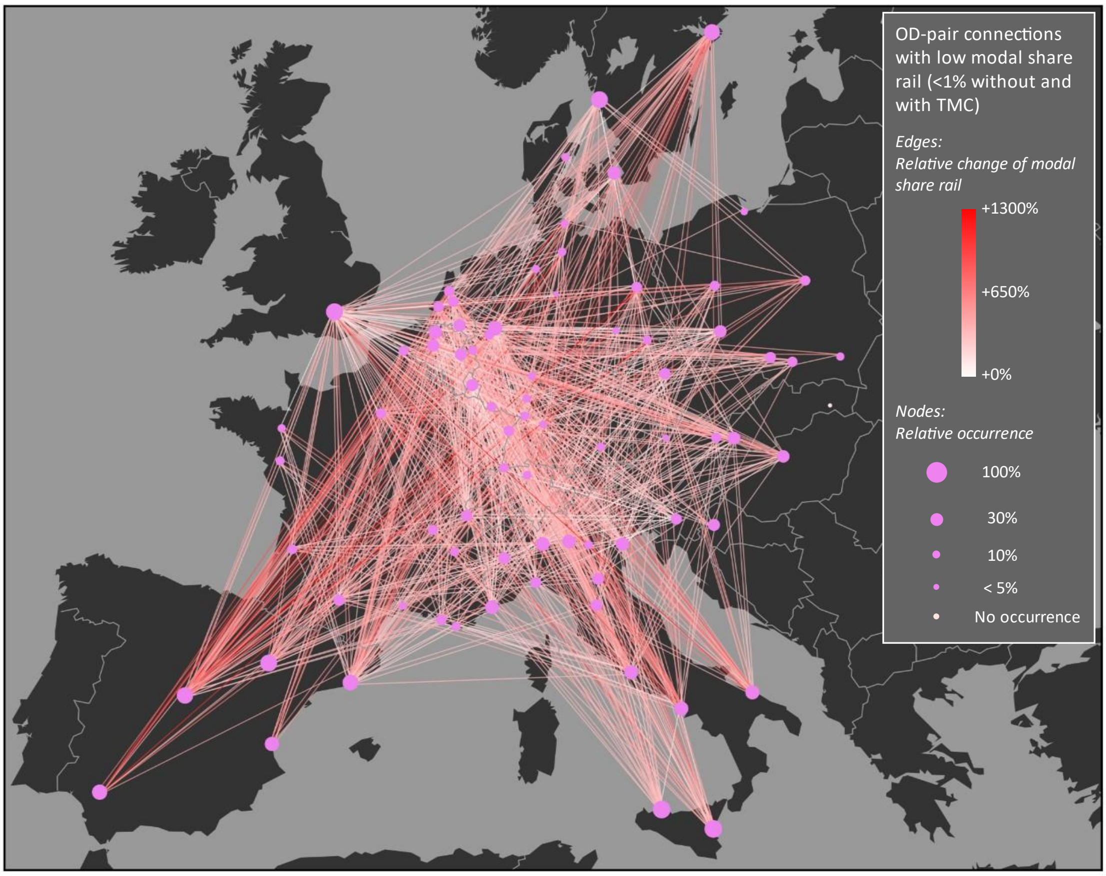


*Figure 43: OD-pair connections with **high modal shift air** (<-20%). Edge colour: Modal share air under TMC. Node size and colour: Relative occurrence per city.*

Second, OD-pair connections are categorised by modal share and modal shift of rail. Figure 44 above shows OD-pair connections where rail remains not competitive at all, as under TMC they still have a modal share below 1%. With 31%, this is the case for almost a third of all OD-pair connections. The map nearly shows the same picture as Figure 42 below with the OD-pair connections of an air modal share above 99%, and argumentations can be transferred. The difference is that the category here additionally includes OD-pair connections where car travel is predominant and also remains predominant under TMC. This is mostly the case for OD-pair connections where on the one hand, air is not competitive due to short distances, and on the other hand, rail is not competitive because the cities are not well connected, and travel time is therefore much higher than for car. Verona-Ljubljana or Grenoble-Nice are typical examples of such OD-pair connections. With an average trip cancellation rate of 26%, the demand reduction within this category is almost as high as for the category of air modal share above 99%.

Figure 44 below shows the 12% of OD-pair connections where the rail modal share is already without TMC higher than 50%. OD-pair connections with a near-monopoly of rail are rare. However, for them, the TMC does hardly induce a modal shift since a large part of travellers already chooses the most sustainable mode. 6% of the OD-pair connections within the category of rail share above 50% are of a distance above 1,000km, in contrast to 18% from all OD-pair connections. Consequently, high distances are underrepresented but they do exist (for instance Bordeaux-Hamburg or Bologna-Kiel). On the one hand, it is noticeable that countries with a high-speed rail network – France, Italy, Germany, and Spain – have a relatively high relative occurrence. On the other hand, high-speed rail turns out to not be the only driver for a high rail modal share, since several other cities' relative occurrence is high as well (for instance cities in Eastern Europe). The modal shift of rail is relatively high for OD-pair connections of this category (for most around 20-30%, see the colour of the edges). So, the TMC induces a relatively high modal shift towards rail for OD-pair connections on which rail already holds the majority of the market in the initial situation.



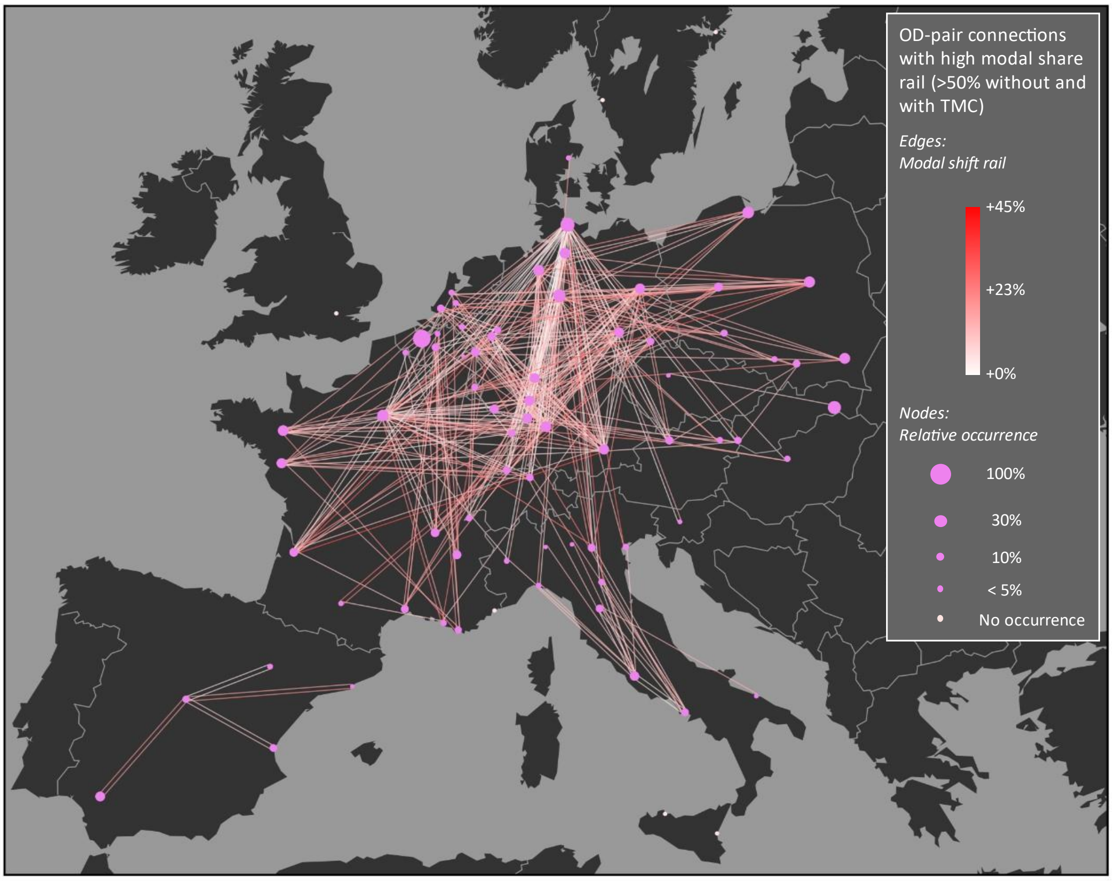


Figure 44: Above: OD-pair connections with ***low modal share rail*** *(<1%). Below: OD-pair connections with* ***high modal share rail*** *(>99%). Edge colour: Relative change of modal share rail (above), modal shift rail (below). Node size and colour: Relative occurrence per city.*

Figure 45 shows the OD-pair connections with a high rail modal shift (more than an increase of 20%). It is noticeable that this category contains nearly the same OD-pair connections as the category of high modal shift air. Hence, argumentations are alike. The initial rail modal share of the OD-pair connections within the present category is in a range of about 10 to 50%, and their rail modal share under TMC is in a range of about 30 to 80%. Hence, as can be seen in Figure 45, TMC makes rail predominant on OD-pair connections where rail is already competitive without TMC, but air is predominant without TMC. 16% of the OD-pair connections within this category have a modal shift of more than 30%. This is often the case for connections where high-speed rail is available or partly available. Examples are Bologna-Paris with a rail modal share increase from 34 to 67% and Venice-Hannover with an increase from 34 to 66%. Even though rail is not expected to be competitive for distances above 800km (see graph with modal split depending on distance, Figure 35 above), more than half of the OD-pair connections within this category are above 800km. Consequently, TMC induces the highest modal shifts towards rail on OD-pair connections where in the initial situation rail is not even expected to be a relevant mode. Under TMC, the role of high-speed rail becomes more important as more demand shifts towards rail where high-speed rail is available. Again, cities in eastern Europe have a high occurrence due to the low VTT in these countries.

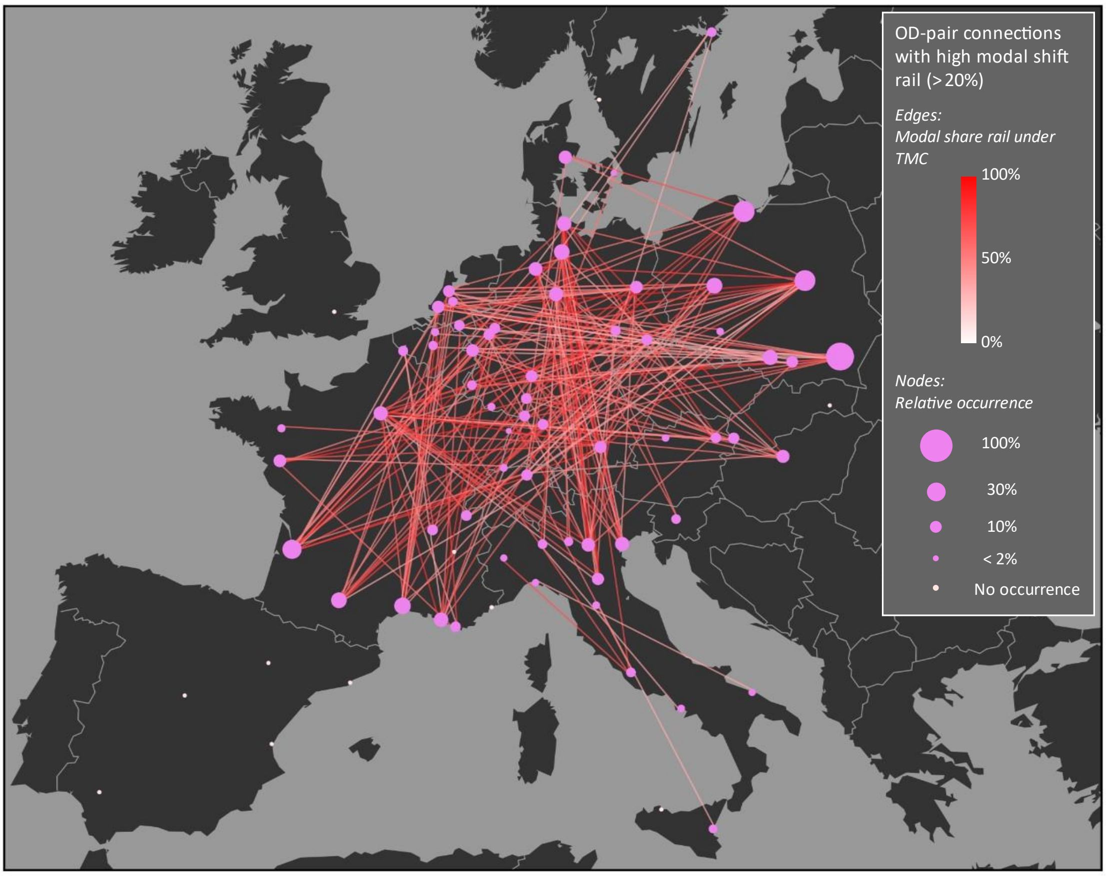
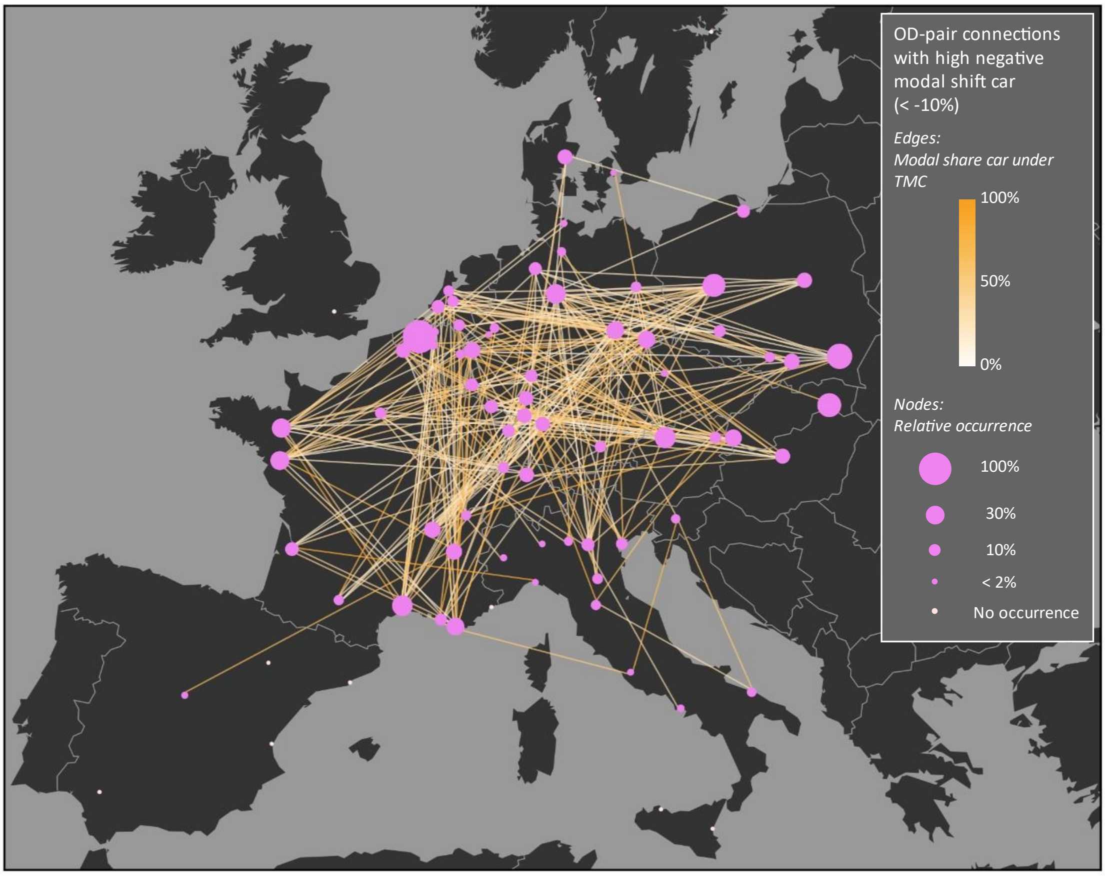


*Figure 45: OD-pair connections with **high modal shift rail** (>20%). Edge colour: Modal share rail under TMC. Node size and colour: Relative occurrence per city.*

Third, OD-pair connections are categorised by modal share and modal shift of car. Maps of OD-pair connections with very high and very low initial modal share and modal share under TMC are not shown because they do not provide further insights. The category of OD-pair connections with less than 1% car modal share both with and without TMC is comparable to the one with less than 1% rail share and the one with more than 99% air share (see Figure 42 below and Figure 44 above). This category consists of long-distance routes where car cannot compete. A map of the category of OD-pair connections with car shares above 80% would show a similar picture as Figure 42 above (low modal share air). They differ in the way that the latter contains OD-pair connections with a predominance of rail, while the category with high car share does not. On all OD-pairs included in the category with high car share, car nearly outperforms rail because either distance is very short, rail travel time is very high, or rail travel time is comparable to car travel time but train tickets are expensive.

Figure 46 above shows the OD-pair connections with a high negative modal shift car (<-10%), and Figure 46 below displays the OD-pair connections with a high positive modal shift car (>+10%). The edge colour represents the car share under TMC. For both cases, it can be identified that the modal share of car under TMC is relatively high. Nearly all OD-pair connections from both categories hold an initial car share of more than 20%. This shows that a high shift towards car only happens on routes where car already has a certain modal share. As the increase and decrease of car share never exceed 20%, the impact of the TMC on the car share is much smaller than on air and rail share.

The difference between these two categories is that OD-pair connections with a high increase in car modal share are of longer distance than OD-pair connections with a high decrease in car modal share. The reason for this is that on longer routes, travellers primarily shift from air to car which leads to an increase in the car share. With a car share increase of 12%, Rotterdam-Zaragoza (1.263km) is the longest OD-pair connection with such a high increase in car share. On shorter routes, travellers shift from car to rail which decreases the car share. For instance, this is the case for Basel-Lille which is only 462km and holds a car share decrease of well 10%. The latter can also be seen by comparing the map of high negative modal shift car (Figure 46 above) with the map of high modal shift rail (Figure 45). They include similar OD-pair connections, which indicates that there is a large shift from car to rail.



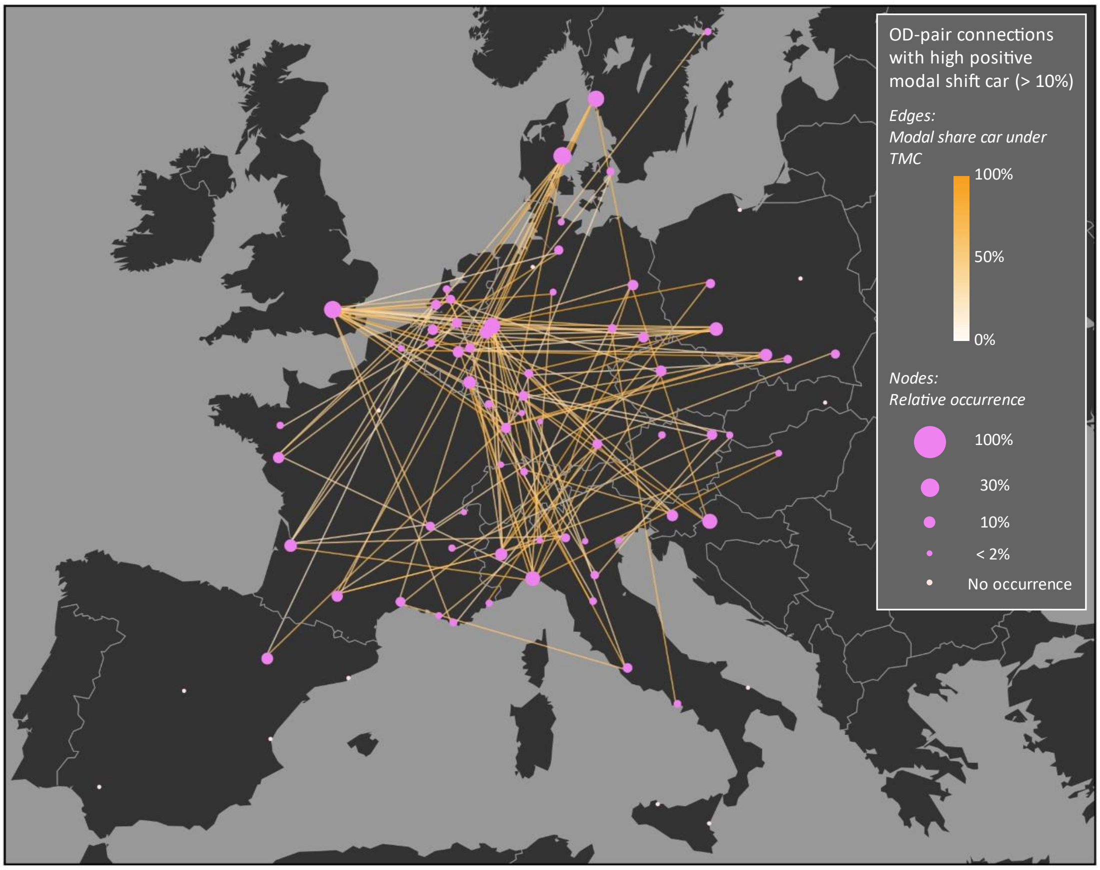


Figure 46: Above: OD-pair connections with ***high negative modal shift car*** *(<-10%). Below: OD-pair connections with* ***high positive modal shift car*** *(>+10%). Edge colour: Modal share car under TMC. Node size and colour: Relative occurrence per city.*

5.3.2. Emissions

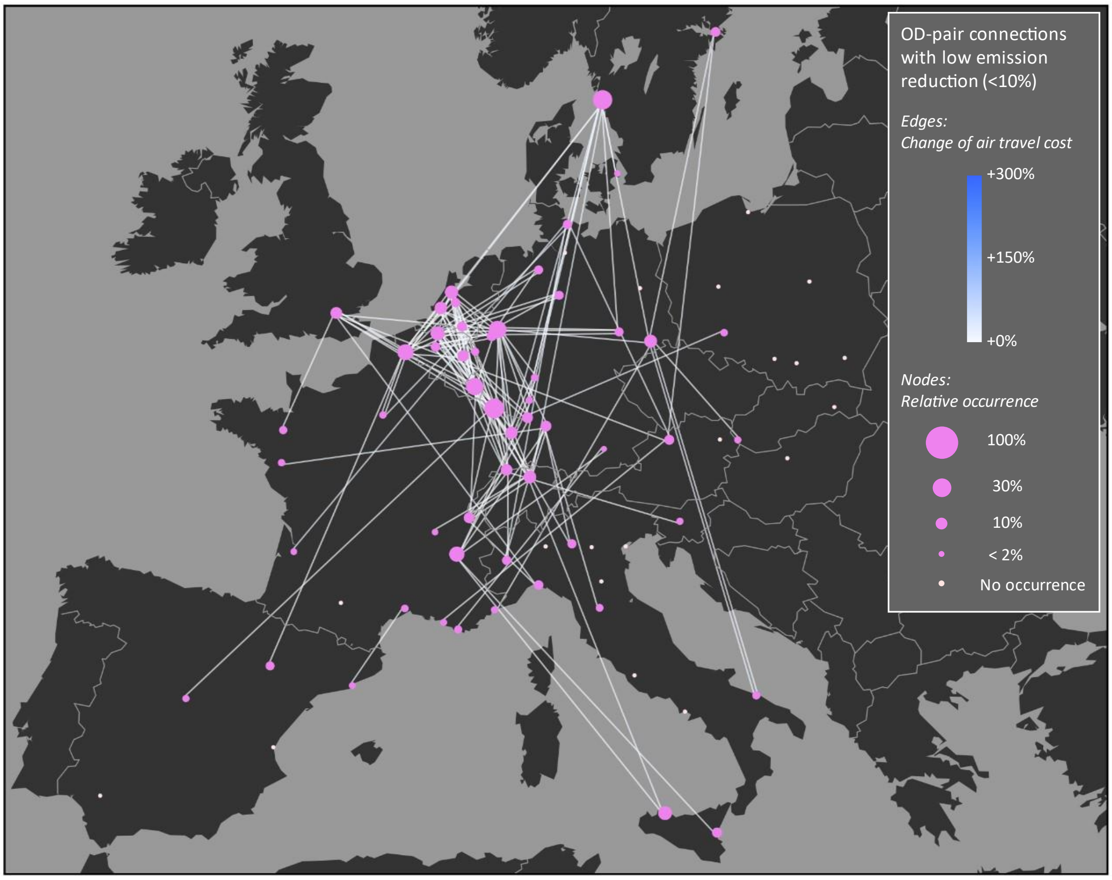
This section investigates which OD-pair connections hold a particularly high or particularly low emission reduction induced by the TMC. Table 11 provides an overview of the two categories according to emission reduction – emission reduction below 10% and emission reduction above 50%.

Table 11: Categorisation of OD-pair connections by low and high emission reduction

Categorisation	Initial situation	Situation under TMC		Number of OD-pair connections (share of all OD-pair connections)
By emission reduction	no requirement	low	< 10%	138 (5%)
	no requirement	high	> 50%	114 (4%)

In Figure 47, maps showing these two OD-pair connection categories can be seen (high emission reduction above, low emission reduction below). The colour of the edges represents the relative increase in travel costs due to the TMC (share of credit costs from total travel costs). Figure 47 above makes clear that most OD-pair connections with a low emission reduction are either long-distance (e.g. to or from Sweden and Sicilia) or short-distance. A low emission reduction is the consequence of a restrained modal shift and trip cancellation rate. A very low modal shift for the case of the OD-pair connections of long-distance happens because travel times for rail are very long. So, even if air travel becomes proportionally more expensive than rail travel, rail is still not competitive. These OD-pair connections are characterised by high flight ticket prices. Therefore, the relative change in air travel costs due to the TMC is small (see node colours in Figure 47 above). For all these OD-pair connections, the credit costs are below 30% of the initial travel costs. This causes a small trip cancellation rate and therefore a low emission reduction. For the short-distance OD-pair connections within this category, the reason for a very low modal shift lies in the modal share of rail which is high from the beginning. Hence, including the credit costs in the travel costs does not strongly affect the mode choice on these OD-pair connections because a high shift towards rail is simply not possible anymore. Also, the trip cancellation rate is low because credit costs for rail travel are low compared to initial travel costs. Many of these OD-pair connections are between cities in Belgium, Luxembourg, the Netherlands, the western part of Germany and the northern part of France - cities which are close to each other, and which have a high level of rail service.

Figure 47 below shows that most OD-pair connections with a high emission reduction are long-distance and therefore have a high modal share of air travel. Primarily cities which are located rather at the edge of the perimeter have a high relative occurrence of connections. These are cities in Spain (Sevilla, Madrid, Valencia, Barcelona), southern Italy (Catania, Naples, Bari), Hungary (Budapest), Poland (Warsaw, Gdanks), Sweden (Gothenburg) and the United Kingdom (London). These cities hold a relatively high share of long-distance OD-pair connections with a high air modal share. Furthermore, Figure 47 below shows that all OD-pair connections within this category have a high increase of air travel costs. This is the case because the initial travel costs are relatively low (often low-cost flights), and the credit costs are high (long distances). For all OD-pair connections, the credit costs are higher than the initial travel costs, which causes a strong decrease in air travel demand (high trip cancellation rate). Many of the mentioned cities (in Poland, Hungary or southern Italy) are less wealthy than central European countries. This might be an additional reason that they are strongly represented in this category as flight tickets there are relatively cheap due to the lower price level. To conclude, an emission reduction above 50% is mainly the consequence of a high trip cancellation rate, and not of a high modal shift towards rail. OD-pair connections which hold high modal shifts are not represented in the two maps of Figure 47. Since a large part of the demand is shifted instead of reduced, the trip cancellation rate for these OD-pair connections is not high enough to achieve an emission reduction of more than 50%. It is found that the OD-pair connections which hold the highest modal shifts towards rail hold an emission reduction of 30 to 50%.



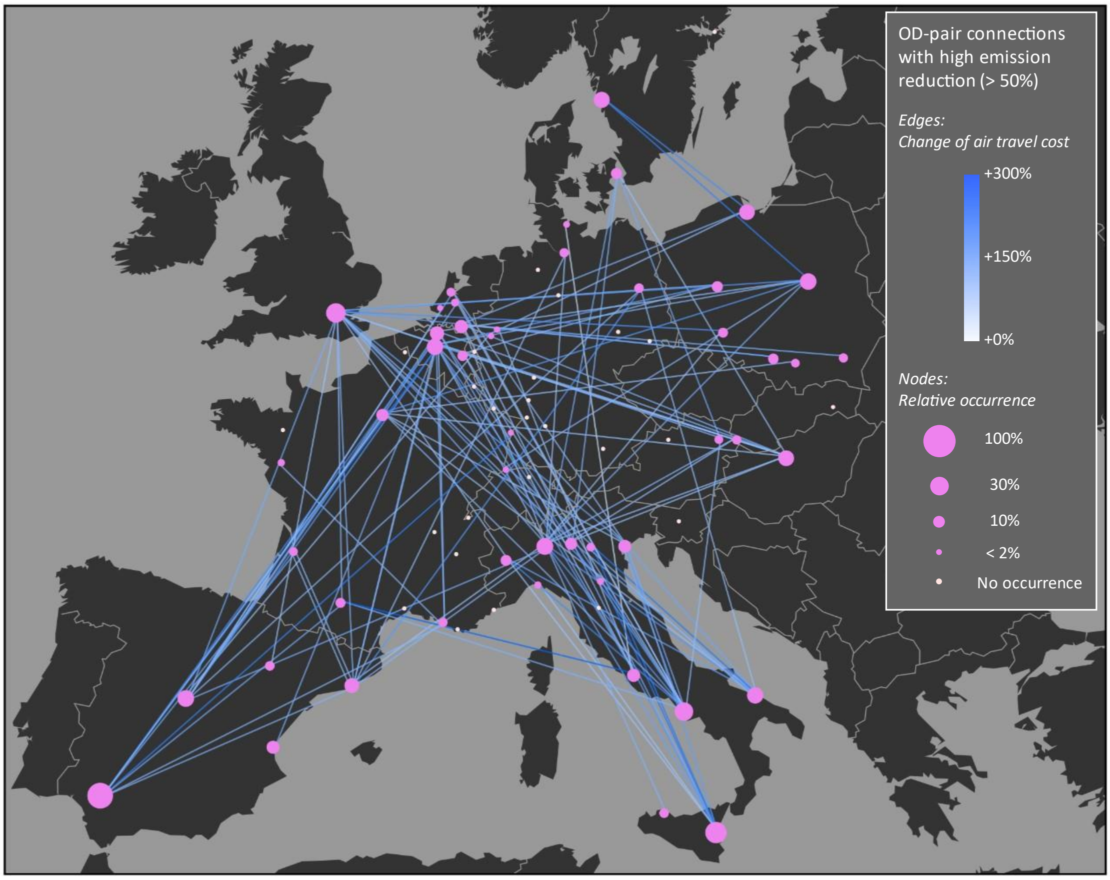


Figure 47: Above: OD-pair connections with ***low emission reduction*** *(<10%). Below: OD-pair connections with* ***high emission reduction*** *(>50%). Edge colour: Relative change of air travel cost. Node size and colour: Relative occurrence per city.*

5.3.3. Trip Cancellation Rate

This section analyses OD-pair connections experiencing hardly any reduction in demand and experiencing a particularly high reduction in demand. The categories according to trip cancellation rate are illustrated in Table 12.

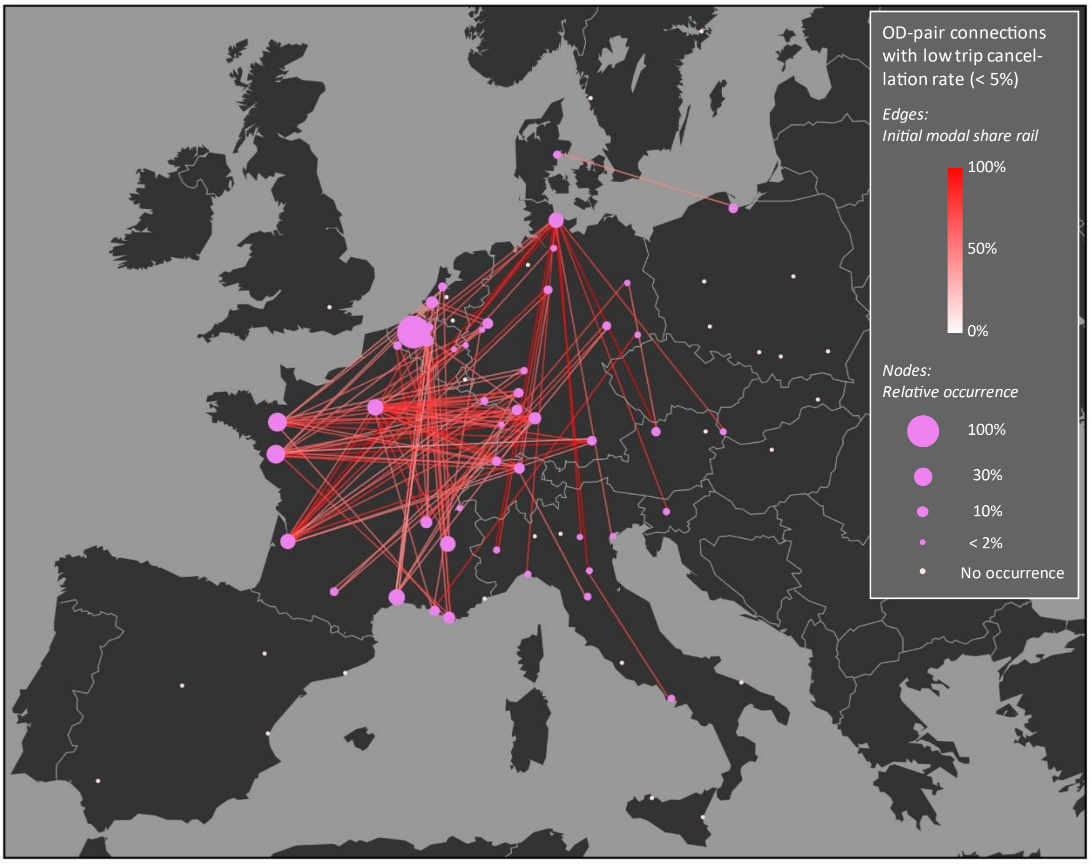
Table 12: Categorisation of OD-pair connections by low and high trip cancellation rate

Categorisation	Initial situation	Situation under TMC		Number of OD-pair connections (share of all OD-pair connections)
By trip cancellation rate	no requirement	low	< 5%	118 (4%)
	no requirement	high	> 50%	112 (4%)

Figure 48 shows maps with all OD-pair connections holding a trip cancellation rate of less than 5% (map above) and of more than 50% (map below). The colour of the edges represents the modal share of rail (initial situation without TMC).

A low trip cancellation rate can firstly be explained by a high initial modal share of rail. Figure 48 above shows that this is the case for all OD-pair connections in this category. All these OD-pair connections have an initial rail modal share of more than 35%, and for 91% of these OD-pair connections, it is more than 50%. Secondly, a low trip cancellation rate can be explained by a low air modal share and a low relative change of air travel cost. 90% of the OD-pair connections have an initial air modal share of less than 20%. For the remaining 10%, the increase in travel costs due to the TMC is below 40%. Primarily cities in western central Europe have OD-pair connections with a low trip cancellation rate. Cities in France (Rennes, Nantes, Montpellier, Grenoble, Paris) and Belgium (Gent) have a particularly high relative occurrence of more than 20%. Most OD-pair connections are of short to medium distance. These are the ones which mostly have a high rail modal share. OD-pair connections of very short distances are not well represented in this category as they often have a high car modal share. Therefore, they have a higher relative increase in travel costs when credit costs are added which results in a higher trip cancellation rate.

Figure 48 below illustrates all OD-pair connections with a high demand decrease (more than 50%) induced by the TMC. It shows nearly the same picture as the map with all OD-pair connections holding an emission reduction of more than 50% (Figure 47 below): In contrast to the OD-pair connections with a low trip cancellation rate, on these OD-pair connections air travel always has a monopoly. They have a very low initial modal share of rail – all have a lower rail share than 10%, and 90% have a lower rail share than 1% – and car is not competitive either. As for the OD-pair connections with an emission reduction above 50%, the trip cancellation rate comes from the low initial air travel costs which cause a high demand reduction in air travel and therewith for total demand as air modal share is high.



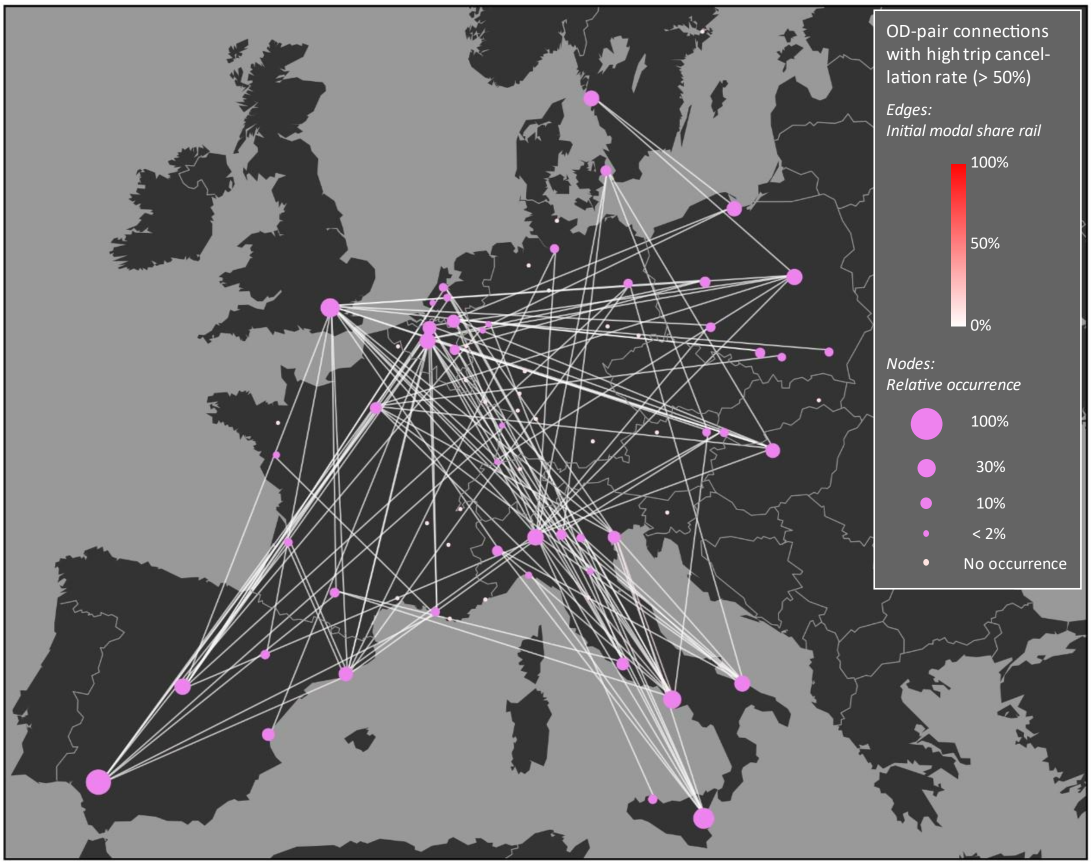


Figure 48: Above: OD-pair connections with ***low trip cancellation rate*** *(<5%). Below: OD-pair connections with* ***high trip cancellation rate*** *(>50%). Edge colour: Relative change of air travel cost. Node size and colour: Relative occurrence per city.*

VI. Conclusion

GHG emissions are responsible for climate change. Strong reductions of these emissions are required in the next years to achieve the goals set by the Paris Agreement. Long-distance passenger transport causes a large share of total GHG emissions and must therefore also strongly decrease its emissions. Existing policy instruments are not effective enough to achieve the required emission decline. The Tradable Mobility Credit Scheme is an alternative to existing policy instruments. As a market-based mobility demand instrument, externalities can fully be internalised. A chosen emission cap assures that the emission reduction target is achieved. In the last years, research in mobility demand has focused on further developing this instrument, whereby the focus has mainly been set on a national perimeter of the TMC. The presented study enlarged the perimeter of the TMC to a large part of the European continent and investigated the implications of the TMC on travel behaviour. The main research objective of the thesis was to estimate the *impacts of the TMC on the modal split between air, rail and car for long-distance leisure travel in Europe*. To do so, a review of the relevant literature was undertaken (chapter II). Next, the methodology (chapter III) was developed: after specifying the TMC, behaviour elements and dynamics were identified to understand the implications of the TMC on travel behaviour. With help of these insights, a mode choice model was created. Therefore, specifications of the modes, the routes and OD-pair connections as well as the users were explicated. Identified as the most important variables, travel time and travel cost were chosen to be incorporated into the mode choice model. Then, the steps to estimate the initial modal split as well as the modal split under TMC were illustrated. In the case study (chapter IV), a set of routes was selected. Data collection (web scraping and data from datasets) was undertaken to characterise the OD-pair connections and to obtain socioeconomic data. Chapter IV provided the results obtained from the case study.

In the following, the research questions are answered in section 6.1. Next, the assumptions and limitations are discussed and recommendations for further research are provided in section 6.2. Last, recommendations for practice (section 6.3) are provided.

6.1. Research Questions

This section aims to answer the research questions introduced in section 1.3. Questions 1.a. and 1.b. deal with existing policy instruments and their comparison to TMC, to provide an overview of the relevance of this study. The questions can be answered with help of the literature review.

1.a. Which policy instruments to reduce GHG emissions have been realised?
1.b. What are the differences to a TMC?

Policy instruments aim to set the right incentives towards more sustainable mobility behaviour. Nowadays, taxes are the most often applied instrument in both road transport and aviation. They reduce externalities but also serve as a source of revenue for the government. In road transport, periodic vehicle ownership taxes, vehicle registration taxes, tolls and vignettes, fuel excise duties and VAT are commonly implemented in Europe. Taxes are also applied for aviation – on seats, flights, fuel and flight tickets. Depending on the country, tax levels differ strongly. Aviation is generally undertaxed due to (lack of) international rules and agreements. More realised policy instruments in aviation are the EU emission trading system (ETS) and carbon offsetting (CORSIA scheme). The ETS is comparable to TMC, but the firms trade the emission rights, while under TMC individual people do it. Also, in contrast to TMC, under ETS the total emissions can be exceeded.

TMC is seen as a promising instrument to reduce the externalities from emissions more entirely. Conventional policy instruments could be fully replaced by TMC. This could cause financial problems for governments as revenues would fall away. But exactly because of that it could be socially more accepted. It could be perceived as fairer, and people could even financially benefit. Furthermore, equity issues can be addressed by variable credit allocation. Under TMC, the credit price is dynamic and adjusts to supply and demand. For taxes, it is the other way around – fixed price and no limit on total emissions. Studies had found that the effectiveness of TMC is equal to or even beyond the effectiveness of other financial incentives with equivalent costs.

The first two sub-questions of the second set deal with travel behaviour induced by TMC and the implications of travel behaviour on the emerging credit price.

2.a. How do travel behaviour and credit market behaviour interact?
2.b. How does travel behaviour (especially mode choice) influence the credit price?

It was found that the credit price affects both the travel behaviour and the trading behaviour on the credit market. An overview was illustrated in Figure 12, section 3.2. A high credit price leads to a growing incentive to sell credits, a low credit price reinforces credit purchasing. Simultaneously, the credit price influences travel behaviour. A high credit price and the therewith high incentive to sell credits increase the willingness to reduce CO_2 emissions, to save credits. Travellers do so by shifting to more sustainable modes, by shifting to shorter routes or by cancelling their trips. A low credit price and the therewith low incentive to sell credits or easiness to buy credits decrease the willingness to reduce CO_2 emissions. Travellers would less often shift to more sustainable modes or shorter routes and would less often cancel trips. Furthermore, the credit price does not only influence travel behaviour but also the other way around. A changed travel behaviour changes the CO_2 emissions and therewith the credit demand. Since the credit price adjusts to credit supply and credit demand, a changed demand alters the credit price. A balancing loop could be identified: an increase in credit demand, for instance, because people want to travel more, leads to an increase in credit need. An increase in the credit need raises the credit price. An increase in credit price increases the modal shift towards sustainable modes, the route shift towards shorter routes and the trip cancellation rate. These changes in travel behaviour decrease the individual's credit expenditure and therewith the total credit demand, so the credit price will decrease again. Therewith, the credit price is always in an equilibrium state.

The third sub-question of the second set deals with the credit price itself:

2.c. How can a realistic credit price be estimated and what is the credit price?

To generate differences in travel behaviour between different citizens, it was decided to make the credit expenditure of a citizen depending on his or her nationality. Therefore, the average net income of each country was used as a proxy for each citizen's CO_2 emissions from long-distance leisure travel, and therewith for credit expenditure. Differences in credit expenditure between citizens of different countries were estimated with income elasticity of demand. Hence, the credit need per citizen and therewith the *credit quantity willing to buy* (CQb) and the *credit quantity willing to sell* (CQs) can be determined. The CQb is the sum of the credit need of all citizens with a credit need higher than zero (citizens who have a credit shortage and want to buy credits), the CQs is the sum of the credit need of all citizens with a credit need below zero (citizens who have a credit excess and want to sell credits). The credit price is estimated by comparing the CQb with the CQs in the market. The goal is to achieve a credit price equilibrium, which means that CQb and CQs are equal. Therefore, the bigger the difference of CQb and CQs, the more the credit price needs to be changed. The price is raised if there is a shortage of credits (CQb bigger than CQs) and declined if there is an excess of credits in the market (CQb smaller than CQs). It has to be assumed that the market clears at all times and that people spend all credits within one allocation period.

With this methodology, reasonable credit prices based on the modelled credit need could be estimated. The credit price depends on the emission reduction target. The higher the target, the lower the credit supply and the higher the credit price. For the case study, a reduction target of 30% was chosen. Under this target and the inclusion of trip cancellation (assumption of elastic demand), the credit price was found to be 193€ per ton of CO_2. This credit price means that travelling for instance from Zurich to Amsterdam (606km) would become 31€ more expensive if travelling by plane, 5€ if travelling by train and 19€ if travelling by car. With a reduction target of 10% the credit price is 62€ per ton of CO_2, with a target of 50% it is 361€. Credit costs emerging under reduction targets between 10% and 30% coincide with the costs of CO_2 emissions found in the literature. Credit prices obtained under the assumption of inelastic demand turned out to be unrealistic. They are around four times higher than under elastic demand.

The two first sets of sub-questions served as a preparation to finally answer the main research objective. Associated with the objective is the third set of sub-questions which investigates the impacts of a TMC on travel behaviour. The main objective – estimating the modal shift due to the TMC – is in the following answered by responding to the first sub-question:

> *3.a. What is the modal split for different European long-distance routes, without and with TMC?*

On average for all the investigated OD-pair connections, the modal split is composed of 50% air travel, 23% rail travel and 27% car travel. Due to the TMC, 17% of the trips are cancelled. From the remaining trips, the share of air was found to be 38%, the share of rail 32% and the share of car 30%. Consequently, there is a modal shift of 12% away from air, a modal shift of 11% towards rail and a modal shift of 3% towards car. On the one hand, there is a shift from air to rail and car and on the other hand, there is a shift from car to rail.

The modal shares strongly depend on travel distance. In the initial situation as well as under TMC, rail and car share the market for the shortest distances. The longer the distance, the larger becomes the modal share of air. In the initial situation, the break-even point of air and rail share is at 500km, and rail share surpasses car share at 600km. This applies to the average (many OD-pair connections strongly deviate). The found values are lower for rail and higher for car compared to other studies. On the one hand, this can be explained by that in the presented study it was assumed that everybody has a car available. On the other hand, only variable costs (fuel and toll) and not the full lifecycle costs were incorporated into the car travel costs. Under TMC, the break-even points of the modal shares move to the right (to longer distances). For air and rail, the break-even point is 600km, for air and car, it is 650km. Consequently, the TMC enlarges the market where rail (and to a less extent also car) can potentially compete with air. Furthermore, it could be found that the modal shift towards rail due to the TMC is largest for medium distances, while for air all distances are similarly affected. On average, the TMC induces a slight decrease in car share for short distances. For medium and long distances, car share remains nearly the same. For all OD-pair connections, TMC causes a decrease in air share and an increase in rail share. Depending on the OD-pair connection, the TMC causes either an increase or a decrease in the car share. If the shift from air to car is larger than the shift from car to rail, it is an increase, otherwise a decrease. These results were found under the chosen value for price elasticity of demand. Under inelastic demand (value of 0), the extent of the modal shifts is several times larger since there is no trip cancellation. Hence, the complete reduction of emissions must be achieved by the modal shift. A higher negative price elasticity of demand than chosen would dampen the impact of the TMC on the modal split.

Focusing on selected routes and categorising routes showed that the impacts of the TMC on the modal split strongly vary between OD-pair connections. OD-pair connections to or from countries in eastern Europe more often hold high modal shifts away from air and towards rail. The reason for this is that travellers from eastern European countries value travel time lower than travellers from western European countries do, as their income is lower. Hence, travellers from eastern European countries are more cost-sensitive and therefore accept higher travel times to avoid additional costs. For OD-pair connections where air nearly holds a monopoly (which is because rail and car travel times are very high, as for Paris-Madrid), the TMC hardly impacts the modal split. Such OD-pair connections are usually of long distances, which means that mainly cities at the edge of Europe, for instance in Spain and southern Italy, are affected. However, the relative change of rail modal share on these OD-pair connections is often high. The highest changes happen on OD-pair connections where initial rail share is far below 1%, and where rail becomes more competitive compared to car by the introduction of TMC. On OD-pair connections where rail has a near-monopoly, the TMC also hardly has any impact on the modal shift. However, a near-monopoly of rail is only the case for very few OD-pair connections.

In contrast, the TMC strongly affects the modal split on OD-pair connections where the market is highly competitive in the initial situation. For these cases, changes in travel costs due to the inclusion of credit costs cause high modal shifts. For instance, between Amsterdam and Berlin, in the initial situation air is predominant but rail is competitive as well. Under TMC, a large part of travellers shifts from air to rail. This happens primarily for OD-pair connections of medium distances. Hence, primarily cities which are neither at the edge nor in the centre of Europe (like Berlin) have a high relative occurrence. On OD-pair connections where rail is strong or even predominant, but does by far not have a monopoly, TMC induces a further large shift towards rail. This is mostly the case where high-speed rail is available, so it can outperform car travel. For instance, for Zurich-Paris, the rail share is enlarged from 76 to 87% and for Bologna-Paris, with an increase from 34% to 67%, the share doubles. Furthermore, it was found that on the one hand, TMC induces a high decrease of the car modal share on routes which are of shorter distances and where car already has a significant initial modal share. In this case, travellers shift from car to rail. On the other hand, TMC induces a high increase of car modal share on longer routes where car starts to compete better with air (shift from air to car).

To conclude, the more competitive the market the larger the mode shift due to the TMC. This makes sense, as for most OD-connections where rail and car are not competitive at all in the initial situation (due to very long travel times), they will not be competitive either under the TMC. The credit costs are too low that they could compensate for the enormous rail and car travel times.

Sub-question 3.b. deals with trip cancellation:

3.b. How does demand for different modes and routes change due to the TMC?

Demand reduction over all OD-pair connections (total trip cancellation rate) was found to be 17.1%. On the one hand, the value depends on the emission reduction target. If a higher target than 30% was used, demand reduction would be higher, and the other way around. On the other hand, the value is very sensitive to the chosen value for price elasticity of demand. In this study, a value of -0.411 was used. A value closer to zero would lead to a lower trip cancellation rate (notice that a value of 0 corresponds to inelastic demand), which would increase the modal shift. A higher negative value would enormously increase the demand reduction and at the same time dampen the modal shift.

It was found that on average, demand is reduced for air and car, and increased for rail. The magnitude of total demand reduction differs by OD-pair-connection: the higher the share of credit cost from total travel costs under TMC, the higher the demand reduction. On the one hand, the share of credit cost depends on the credit cost itself. Since air has the highest emissions per passenger-kilometre, it has the highest credit costs and therewith the highest demand reduction on average. The range of cancellation rates for air is enormous, from 1% to 100%. The lowest demand reduction happens for rail as credit costs are the lowest, with less than 5% for the majority of OD-pair connections. Trip cancellation rates for car travel are in between air and rail with 8 to 12% for all OD-pair connections. On the other hand, the share of the credit cost depends on the initial travel cost. For car, initial travel costs were assumed to be proportional to travel distance and variations only happen due to fuel price differences in different countries. As credit costs are as well proportional to distance, car trip cancellation rate is relatively constant over all OD-pair connections. Initial travel costs of rail depend on the ticket cost which varies a lot between OD-pair connections. Low-cost flights stand out with very high trip cancellation rates as credit costs hold a high share of total travel costs.

Since cancellation rates of air trips are much higher than those of rail trips, the lowest trip cancellation rates happen on OD-pair connections where the initial rail modal share is high and the initial air modal share is low. It could be found that central European cities in France and Belgium have a lot of OD-pair connections with low trip cancellation rates. This is reasonable, as they are well integrated into the rail network and have many connections of a relatively short distance. In contrast, the highest trip cancellation rates happen on OD-pairs where rail and car can hardly compete with air due to their very long travel times.

The last two sub-questions address the impacts of the TMC on GHG emissions.

3.c. What is the GHG reduction for different routes caused by the modal shift and change in mobility demand, due to the TMC?
3.d. How does the proposed TMC contribute to the GHG emission reduction target?

The total GHG (resp. CO_2) reduction induced by the TMC is equal to the emission reduction target, which was chosen to be 30% in this case study. However, the emission reduction and the change of emissions per passenger-kilometre vary between OD-pair connections. Low emission reduction happens on OD-pair connections where modal shift and trip cancellation rate are restrained. This is either the case for short distances, where there is hardly any potential left to shift to rail (mainly between cities in central Europe), or for very long distances, where even under TMC rail and car cannot compete with air, and at the same time trip cancellation rate is low because flight ticket prices are very high. The highest emission reduction (above 50%) happens on OD-pair connections of long distances where the trip cancellation rate is high due to a high air modal share and cheap flight ticket prices. This is mainly the case for cities at the edge of Europe. Furthermore, there are OD-pair connections, like Paris-Madrid, where avoided emissions are high, but emissions per passenger-kilometre do hardly change. This is the case when air remains a near-monopoly and the trip cancellation rate is high.

Emission reduction is partly achieved by modal shift and partly by trip cancellation. Under inelastic demand, where the emission reduction is fully achieved by modal shift, the magnitude of the modal shift is several times larger than under elastic demand. This shows that trip cancellation is to a larger extent responsible for the reduction than the modal shift (assuming the chosen value of price elasticity). As demand is reduced for air and car trips, the share of rail increases due to the TMC, even if there is no demand shift towards rail (if the share of cancelled trips is not included in the modal shift. Therefore, trip cancellation does not only reduce the total emissions of an OD-pair connection, but it also reduces the average emissions per passenger-kilometre of the travellers who still do travel.

Sub-question 3.d. can be shortly answered. The contribution of TMC to the GHG emission reduction target is exactly the emission target itself. In contrast to taxes, under TMC the emission limit is capped by the number of credits that are supplied (allocated in total by the central authority). This is the big advantage of TMC compared to conventional taxes regarding the effectiveness of the policy instrument, as the emission reduction that has been set in a political process is always achieved.

Furthermore, the TMC has social impacts, which were not explicitly mentioned in the research questions. From a social view, the additional costs for a trip in Europe can be seen as feasible. On average, they are 30€ for air, 5€ for rail and 18€ for car trips, which corresponds to the costs when travelling Zurich-Amsterdam (31€ for air, 5€ for rail and 19€ for car). Since long-distance leisure travel is not a basic need, this TMC with an emission reduction target of 30% can be regarded as acceptable. However, the TMC causes some disadvantages depending on the country of residence. The degree of its centrality within Europe is deciding how much he or she is affected negatively by the TMC.

6.2. Limitations and Opportunities for further Research

To simplify the model, several assumptions were made. These assumptions implicate limitations, which are discussed in the following. Therefrom, implications for further research are derived and recommendations for future studies are provided.

Specification of TMC

The perimeter of the TMC is limited to the mainland of Europe and the United Kingdom. This could be perceived as unfair since citizens of for example Cyprus or Malta do not have to spend credits for their flights. In contrast, if islands were also included in the TMC, citizens of these islands would be strongly disadvantaged because they do not have alternatives to travel by plane – except for the boat which has very high travel times. In that case, disadvantages could be mitigated by uneven credit allocation. The chosen perimeter causes the limitation that intercontinental flights are not affected by the TMC. Hence, there will be an incentive to avoid credit costs by flying to an intercontinental destination instead of undertaking a European flight. This might cause a huge increase in emissions.

Further research could extend the study to a worldwide perimeter. Global implementation of the TMC could be reasonable because a large part of transport emissions is from intercontinental flights. Moreover, if the TMC had a global perimeter, circumvention of the credit costs by travelling intercontinental instead of within Europe would be avoided. Applying the mode choice model for a worldwide implementation needs some adjustments of assumptions and specifications. For example, the value of time or the emissions per passenger-kilometre might be different. Other modes like the bus shall be included. For instance in America, bus travel has a much higher relevance because rail is not well developed.

Furthermore, there is a large potential for policy research regarding the TMC. The research could address the way it shall be implemented. For instance, who exactly would fulfil the function of a central authority, how is the credit market organised, how can people access the credit market, which regulations are needed regarding credit hoarding to prevent speculation, or how often shall credits be allocated (every week, every year etc.).

Behaviour Elements and Dynamics

Modal shift, route shift and trip cancellation have been identified as behaviour elements that are affected by the TMC. The mode choice model has the limitation that it does not incorporate route change. Nevertheless, trip cancellation is kind of represented by route change because choosing another destination means that the initial trip is cancelled (mentally), and another trip is booked. Furthermore, there might be more elements in behavioural changes which were not identified. In further research, the modelling of travel behaviour shall be upgraded. Therefore, investigations need to be done about further impacts of the TMC on travel behaviour. An approach to include found impacts in the mode choice model needs to be developed.

The equilibrium state resulting from the balanced loop identified in section 3.2 is dynamic. Demand is influenced by exogenous factors (season of the year, economy etc.) and changes over time. The mode choice model in this study is limited to one point in time. Time could be incorporated by including variables like the season of the year and economic cycle which would dampen or intensify the willingness to travel and therewith the willingness to spend credits.

Specifications of Modes, Routes and Users

For rail travel, access and egress time was assumed to be 20min and access/egress costs were neglected. Since many people live outside of the centre, access and egress time might be much higher on average, and access and egress costs might be significant. This limitation might have led to an overestimation of the modal share of rail. Air access and egress times and costs are custom for each city and airport. It was also assumed that all people live in the city centre. As airports are most times outside of airports, it depends on the traveller's residence place if access and egress times were assumed too low or too high. Car access and egress times were underestimated since not everybody travelling by car has it parked at home. Also, car travel costs were underestimated as it was decided to only include the variable costs. However, a model run including all the full lifecycle costs of the car turned out to be unrealistic as car costs were extremely high and therefore the car modal share was far too low. Furthermore, car occupancy (assumed to be 1.9) influences the results. A full car (4 persons) would more than halve the car credit costs per person, someone travelling alone would experience nearly double the credit costs. The detour factor for rail and car was assumed to be constantly 1.3 resp. 1.2. Mainly rail distances can deviate strongly, especially on hub-oriented high-speed connections where high detours are often accepted because travel time is lower than a direct route with conventional rail. For instance, Lyon-Bordeaux has a detour factor of 2.2 because the fastest connection goes via Paris (measured with Brenschede (2022)). Even though this would almost double the credit costs, it would not much influence the results because the absolute credit costs for rail would still be low. For air, the detour factor was assumed to be zero which deviates from reality for transfer flights. Considering the real detour factor would strongly reduce the demand for air travel on routes which do not have a direct flight.

For air and rail, no differentiation between classes of travel was made. A trip in business or first class causes more CO_2 emissions per passenger-kilometre than the same trip in economy class or second class because fewer passengers can be transported per aircraft or train. It has therefore higher credit costs. If different travel classes were considered, TMC would not only cause a modal shift but also a class shift. Business or first travellers would fly economy, resp. first-class rail travellers would ride second class. The obtained magnitude of mode shift and trip cancellation might be slightly smaller as part of the emissions would be reduced by shifting the travel class.

Not only for a worldwide perimeter of the TMC, including more modes could be meaningful. Also in this study, including long-distance bus (coach) travel would have provided a more complete picture of the impacts of the TMC. The CO_2 emissions per passenger-kilometre of bus travel are in a range between 0.028 kg and 0.089 kg (carbonindependent, 2022). Hence, it has most probably higher emissions than rail (0.029kg) but lower emissions than car travel (0.116kg) and could therefore play an important role when flights are substituted. Especially on routes where rail is not available or rail travel times are very high, demand could be shifted to bus instead of car. Consequently, the trip cancellation rate would be lower than estimated on these routes.

For the airport choice, this study assumed that only airports with an access/egress time of less than one hour are feasible. In some cases, good options could have been left out. For instance, travelling from Zurich via Basel airport is often cheaper because Basel is served by low-cost carriers. The all-or-nothing assignment in the airport choice is a strong simplification, as travellers would be spread over several airports.

User activities were limited to receiving, spending, buying and selling credits. However, users could also neither spend nor buy credits – hoard credits. Possible reasons for that are speculation – hoping for a higher value in the future to sell them later – or the willingness to conserve them for planned future trips. User characteristics were simplified by unitising income and therefore credit expenditure of all citizens of the same country. Even though there are large differences in income and credit expenditure within a country, this simplification is expected to not have changed the results a lot. As 36 countries are incorporated, there is a big variety of incomes. Finally, the variety of income is only used to estimate the CQb and CQs. Hence, differentiating users in more detail between higher- and lower-income users would cancel each other out.

The trip purpose was limited to leisure. The incorporation of other trip purposes would require that different VTTs are used – higher VTTs for business and commuting trips. Also, the price elasticity of demand would have to be increased for these trips as business and commuting travellers are less price-sensitive than leisure travellers. A higher VTT would decrease the modal shift due to TMC and a higher price elasticity would decrease the trip cancellation rate. Consequently, the credit price would increase. It is recommended to include more trip purposes in future studies. Hence, a more complete picture of the impacts of a TMC on the modal split and demand reduction could be obtained.

In transport literature, there is limited understanding of long-distance travelling. Therefore, this study estimated the modal split based on travel times and travel costs only, as studies have shown that these are most relevant when choosing a mode. However, other variables like the number of transfers, comfort level and frequency also play a role. These were neglected to simplify the data collection, and because a set of parameters fitting for European long-distance travel was hardly findable in the existing literature. Accordingly, alternative specific constants were set to zero. The variable which could have most changed the results if it was included might be car ownership. In this study, it was assumed that everyone has a car available. This leads to a strong overestimation of the initial car modal share.

Accordingly, apart from research about TMC, there is a large potential to research long-distance travel in the European context. Studies including sets of parameters of mode choice variables of all relevant travel modes, as well as elasticity values of all relevant travel modes are needed. They will be valuable for further research – for instance about TMCs – where results from those are could be used.

VTT was made dependent on the origin and destination country of a route. Therefore, it was assumed that all travellers origin from these two countries, with the same ratio as the population of these countries. However, part of the travellers might originate from other countries, which would change the VTT on the route. VTT was not differentiated by modes and trip components. If it was, the initial modal split would hold a higher rail and a lower air and car share. On the one hand, VTT on the train is lower as time can better be used for working or enjoyment. On the other hand, the in-vehicle VTT is lower than the access, egress and waiting VTT, and rail trips have a higher share of in-vehicle time from total travel time than air trips. Therefore, focusing on the *worthwhile travel time* (see section 2.3.8) could be a reasonable approach to assess and better differentiate the VTTs.

CO_2 Emissions

The CO_2 emissions per passenger-kilometre for each mode were simplified. Air emissions were assumed to be constant for distances below 400km and above 1,000km. For distances in between, a linear decrease in emissions was assumed. In reality, emissions decrease about exponentially with distance. Therefore, very short distances would have higher credit costs than estimated and would therefore even more pushed out of the market due to the TMC. Furthermore, different airlines have different types of airplanes and fleet ages which have different fuel consumption and therewith emissions. For instance, a trip with an airline that has already replaced the Airbus A320 with the A320neo (new engine option) holds up to 20% fewer emissions than a trip with an airline that has not (Flugzeuglexikon, 2022). Rail and car emissions were assumed to be constant. Regional differences in electricity production and propulsion energy for rail as well as car size and age were not respected. On routes where rail is not electrified, the rail credit costs would increase, which would reduce the modal shift towards rail.

This study did not consider the global warming effect. 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). It is recommended that the global warming effect is incorporated into further research. Then, credit costs would be much higher for air trips, which would lead to a higher modal shift away from air and a higher cancellation rate of air trips.

In the future, the emissions per passenger-kilometre are expected to change. While rail emissions will only slightly decrease after decades (due to new rolling stock), car emissions are being reduced strongly these years through electrification and alternative propulsion like hydrogen. If this was included in the model, there was a higher modal shift from air to car, a lower shift from car to rail, and a lower trip cancellation rate of car trips. However, if all emissions are included (for example also those from the battery production), these changes in the results are dampened. The emissions of air trips are being reduced continuously, but much slower, by fleet modernisation. Sustainable flying is not expected to be realised in the next years or decades. However, if this was possible in the future or at least emissions were reduced drastically, the impact of the TMC on the air modal shift would as well be strongly reduced.

Credit Price Dynamics

For simplification, credit expenditure per user was derived from the income elasticity of demand and therefore only depended on the net income of the user’s nationality. Even though the literature review illustrated that income is a good proxy, many more factors influence credit expenditure: age, household size, if someone has an urban lifestyle, accessibility of the place of residence, etc. Furthermore, it was assumed that someone’s CO_2 emissions are proportional to his or her extent of long-distance travelling.

To estimate the credit price, it was assumed that all credits which are not used are brought into the market, traded and then spent by the new owner. However, there would be credits which are not sold, since for the current credit price potential sellers are not willing to sell (only if the price was higher) and potential buyers are not willing to buy (only if the price was lower).

On the one hand, to incorporate the impacts of the TMC into the utility functions, the credit costs were simply added to the initial travel costs. On the other hand, in this study, it was assumed that credits are always traded and spent. Hence, credit hoarding was neglected. To obtain a better understanding of how the TMC influences utility functions, it is recommended that future studies incorporate trading behaviour into the model. Therefore, the trading process could be modelled, for instance, using agent-based modelling. Behavioural effects that are expected under TMC, amongst others loss aversion, shall be investigated and included in the model. For instance, loss aversion could be considered in the model by distinguishing between travellers who use allocated credits and travellers who use additionally bought credits for their trip. The latter could be faced with higher costs than the firsts, as they face a money loss to buy additional credits, while the firsts only do not face a gain as they use and do not sell the credits. This could be modelled by multiplying the credit costs of travellers who use additionally bought credits by a factor larger than one.

A price elasticity of demand of -0.411 was used to estimate the trip cancellation rate. This value is very sensitive. Modal shift due to the TMC would strongly decrease and trip cancellation rate increase if the value was chosen to be further away from 0, and the other way around if it was chosen to be closer to 0. For the special case of a value of 0 (inelastic demand), it was found that the modal shift is several times higher. Future research shall further investigate the demand elasticity of the credit price.

Case Study

The case study aimed to include 12,321 OD-pair connections (112 cities connected to each other) which belong to the most relevant within Europe regarding trip potential. A main limitation of the case study is that only 2,998 out of the 12,321 OD-pair connections could be included. Mainly OD-pair connections of large distances could not be incorporated because trainline.com did not find corresponding rail ticket prices. Therefore, the average distance of the most relevant long-distance routes in Europe is expected to be higher than found in the case study. Consequently, average air modal share and therefore total demand reduction due to the TMC is expected to be higher.

The estimated initial modal share per route could not be validated with empirical data. For air travel, there is passenger volume data available. However, this study only included leisure travellers, and this data includes all travellers. For rail travel, only national statistics but no demand data for international trips could be found. For car travel, there could no data be found at all. For future studies, it is recommended to validate the modal split if passenger volume per mode can somehow be made available.

Simplifications had to be made to collect ticket prices. No return tickets were considered. This might have led to overpriced flight tickets as they are usually more expensive when only one way is booked. If return trips were included, the initial air share might be higher. Furthermore, collecting ticket prices for different days and different timings of booking would have improved the results. The used methodology led to some extreme results. For instance, for Lille-Zaragoza a flight ticket price of 449€ was scraped which led to an initial air modal share of nearly zero. As the distance of this route is 1.040km, air would be expected to be the predominant mode. By removing such outliers, the accuracy of the results could have been improved. Moreover, the web scraping was conducted for about 10 days, since for each OD-pair connection it took time to load the website. Consequently, it was not fully complied with the timing of the booking chosen to be 45 days in advance. Air ticket prices were scraped first. Hence, the last train ticket prices had a booking timing of about 35 days in advance. This might have led to an overestimation of train travel costs, as prices usually increase towards the date of the trip.

The provided results are based on the emission reduction target which was chosen to be 30%. Under a stricter target, credit price and therefore modal shift and demand reduction would strongly increase. Under a more moderate target, they would decrease. This study investigated the impacts of a TMC on travel behaviour for the year 2023. If the temporal scope was changed to later years (e.g. 2030 or 2040), the emission reduction target would be higher because by 2050 net zero emissions must be achieved. Therefore, modal shifts and trip cancellation rates would be higher if later years were investigated. However, it is expected that due to technological progress emissions per passenger-kilometre will decrease especially for air and car travel. Hence, this increase in modal shift and trip cancellation rates would be dampened. For very high emission reduction targets, the TMC would cause a large part of the trips to be cancelled. In that case, the TMC would certainly not be socially accepted anymore. Consequently, TMC could well be part of the solution to achieve net zero by 2050, but there are other impactful measures required.

6.3. Recommendations for Practice

This section first provides recommendations for the specification of the TMC. Second, recommendations regarding the impacts of a TMC are made. These are recommended actions for different stakeholders, for the time before the implementation of the TMC and during the application time of the TMC.

If a Europe-wide TMC is introduced, it is recommended to choose a uniform credit allocation with credits for free. This allows everyone to travel without additional costs to a certain degree (apart from that there is a hidden cost because credits could be sold). By making the number of credits allocated depending on the individual’s situation, equity issues could be addressed. For instance, more credits could be allocated to people who are dependent on the car because they live in the countryside or to people with lower income because they cannot afford to buy additional credits. But under the assumption that credits only need to be spent for long-distance trips, uneven allocation is not recommended. On the one hand, long-distance travel is, in contrast to daily travel, not a basic need and is not required to reach jobs. On the other hand, the TMC is already an instrument that supports low-income groups. For them, it might be very attractive to sell credits as this could generate earnings which are relatively high compared to their income. In that sense, if people are not willing to undertake long-distance trips, selling credits leads to an unconditional basic income.

It is recommended that the credits needed for a trip depend on the actual emissions of the trip, and not on the emissions that are expected on average when using a certain mode. For instance, if a car with high fuel consumption is used, the credits needed shall be higher than if a fuel-efficient car is used. Therewith, people are incentivised to avoid emissions. Though, this makes the implementation of the TMC more complex. Also, airlines have the incentive to save fuel. They will invest more in a new fleet and will try even harder to have a high seat occupation on their flights, as emissions of a flight are divided by the number of passengers to obtain the emissions per traveller. However, it is recommended that passengers pay the credits estimated by the average seat occupation of the airline and not of the actual flight. Otherwise, if a traveller is on an almost empty flight, credit costs become extremely high, which is not subject to a traveller's own choices. The same shall account for rail travel.

The mode choice model is created in a way that emission reductions are achieved by modal shift and trip cancellation. Hence, there happens a trade-off between modal shift and trip cancellation. The higher the potential to shift demand from air to car and rail and from car to rail, the lower the trip cancellation rate and therewith the reduction of travel demand. If mode shift is not feasible, trips need to be cancelled to not exceed the emission cap. Consequently, under a selected price elasticity of demand, a higher modal shift is better for social welfare as people can still undertake their trips. Therefore, high investments in the European rail network are recommended. With a better rail network, the negative social impacts of the TMC could be reduced, as the potential of the modal shift would increase, and the number of cancelled trips would decrease. It was found that TMC causes an increase in travel demand for rail. To manage to carry all the passengers willing to travel by train, capacity extensions are required. The extensions are especially important for high-speed lines because the largest demand shifts towards rail are expected on medium-distance routes where rail travel is a strong competitor (which is mostly the case for routes where high-speed rail is available).

Hence, the investments in the European rail network shall on the one hand increase the capacity, and on the other hand, enhance the level of service. Thereby, the reduction of travel time is most relevant. First, it could be achieved by providing more direct connections. Therefore, better integration between the national railways is recommended. For instance, no transfers on the Zurich-Amsterdam route (which already exists as a night train but with higher travel time) could reduce the travel time and generally increase the attractiveness of rail travel. Second, travel time reduction could be achieved by upgrading conventional lines to high-speed lines. Furthermore, the attractivity of rail travel could be increased by closer cooperation between the national railways, for instance by offering a conjoint user-friendly booking platform for long-distance trips.

As airlines will lose customers due to the TMC, it is recommended to airlines to decrease the emissions per passenger-kilometre. Therewith, the negative effects of the TMC can be dampened. This can be done by investing in new fleets and alternative fuels. The credit costs of business and first-class flights will be higher than for economy class since the space requirement is bigger and therefore fewer passengers can be carried. Therefore, it might be better to more focus on economy class as a main cabin product. However, business and first-class travellers might also be less cost-sensitive towards credit costs and their relative travel cost increase might not be higher.

When travellers make a mode choice, they often only compare the actual travel times but not how well they can use the time while travelling for work or enjoyment. Hence, since on rail trips travel time can better be used for work or enjoyment, it is recommended for train operators to promote *worthwhile travel time*. For instance, they could display a comparison of *worthwhile travel times* between air, rail and car travel on their website when booking a trip. From a social perspective, focusing more on the *worthwhile travel time* instead of the VTT from an economic view could be an opportunity to dampen the negative impacts of the TMC on the modal split – the increase of average travel time.

VII. References

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

Alberini, A., Bigano, A., Ščasný, M., Zvěřinová, I., 2018. Preferences for Energy Efficiency vs. Renewables: What Is the Willingness to Pay to Reduce CO2 Emissions? Ecol. Econ. 171–185.

Aparicio, A., 2016. Exploring recent long-distance passenger travel trends in Europe. Transp. Res. Procedia 14, 3199–3208.

Arnadottir, A., Czepkiewicz, M., Heinonen, J., 2021. Climate change concern and the desire to travel: How do I justify my flights? Travel Behav. Soc. 282–290.

Autoalan Tiedotuskeskus, 2022. Average age of passenger cars in some European countries.

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

Balzer, L., Provoost, J., Cats, O., Leclercq, L., 2021. Tradable Mobility Credits and Permits: State of the Art and Concepts. Deliverable D4.1.

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

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

Brenschede, A., 2022. BRouter.

Bundesministerium für Digitales und Verkehr (BMDV), 2010. FIS Forschungsinformationssystem, Mobilität in Deutschland 2008 (MiD 2008). Bonn.

carbonindependent, 2022. Emissions from bus travel.

CE Delft, European Commission, 2019. Taxes in the Field of Aviation and their impact (Final Report).

Christensen, L., 2016. Environmental impact of long distance travel. Transp. Res. Procedia 14, 850–859.

Christensen, L., Nielsen, O.A., 2017. What do Europen tourism demand survey tell about long distance travel? Technical University of Denmark, DTU Management Engineering, Lyngby.

de Bok, M., Costa, Á., Melo, S., Palma, V., 2010. Estimation of a mode choice model for long distance travel in Portugal. Faculty of Engineering of the University of Porto, Significance, The Hague (Netherlands).

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

Discover Cars, 2021. Toll roads, bridges, and tunnels around Europe.

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. Transp. Res. Part A 52–64.

Dogterom, N., Ettema, D., Dijst, M., 2017. Tradable credits for managing car travel: a review of empirical research and relevant behavioural approaches. Transp. Rev. 37:3, 322–343. https://doi.org/10.1080/01441647.2016.1245219

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

Europe on Rail, Germanwatch, 2021. European public opinion poll shows support for shifting flights to rail.

European Commission, 2022. A European Green Deal, Striving to be the first climate-neutral continent. European Union.

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

European Environment Agency, 2022. Oil bulletin prices history.

European Environment Agency, 2021. EEA greenhouse gases - data viewer.

European Environment Agency, 2019a. EMEP/EEA air pollutant emission inventory guidebook 2019.

European Environment Agency, 2019b. Data vizualisation, Greenhouse gas emissions by aggregated sector. European Union, Copenhagen.

European Environment Agency, 2019c. Greenhouse gas emissions from transport in Europe. European Union, Copenhagen.

Eurostat, 2022a. Population on 1 January by age and sex.

Eurostat, 2022b. Gross domestic product at market prices.

Eurostat, 2022c. Average hours worked and paid per employee, by working time and NACE Rev. 2 activity.

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

Flugzeuglexikon, 2022. Internationale Luftfahrtausstellung ILA – Berlin Air Show – Passagierflugzeuge und Business-Jets – Airbus A320 neo.

Fontaras, G., Zacharof, N.-G., Ciuffo, B., 2017. Fuel consumption and CO2 emissions from passenger cars in Europe – Laboratory versus real-world emissions. Prog. Energy Combust. Sci. 97–131.

Google, 2022. Google Maps.

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

Heufke Kantelaar, M., Molin, E., Cats, O., Donners, B., van Wee, B., 2022. Willingness to use night trains for long-distance travel. Travel Behav. Soc. 339–349.

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

Investopedia Team, James, M., Kvilhaug, S., 2022. Price Elasticity of Demand Meaning, Types, and Factors That Impact It.

Koppelman, F.S., Wen, C.-H., 2000. The paired combinatorial logit model: properties, estimation and application. Transp. Res. Part B 75–89.

Krenek, A., Schratzenstaller, M., 2017. Sustainability-oriented tax-based own resources for the European Union: a European carbon-based flight ticket tax.

Leiper, N., Witsel, M., Perry Hobson, J.S., 2008. Leisure travel and business travel: a comparative analysis. Asian J. Tour. Hosp. Res. 2(1).

Mabit, S.L., Rich, J., Burge, P., Potoglou, D., 2013. Valuation of travel time for international long-distance travel – results from the Fehmarn Belt stated choice experiment. J. Transp. Geogr. 153–161.

Malichova, E., Cornet, Y., Hudak, M., 2022. Travellers' use and perception of travel time in long-distance trips in Europe. Travel Behav. Soc. 95–106.

Milieu Centraal, Stimular, SKAO, Rijkswaterstaat, 2015. CO2 emissiefactoren.

OECD, 2013. Effective Carbon Prices. OECD Publishing, Paris.

Pagliara, F., Vassallo, J.M., Román, C., 2012. High-Speed Rail Versus Air Transportation, Case Study of Madrid-Barcelona, Spain. Transp. Res. Rec. 10–17.

Petersen, M.S., Sessa, C., Enei, R., Ulied, A., Larrea, E., Obisco, O., Timms, P.M., Hansen, C.O., 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.

Raux, C., Croissant, Y., Pons, D., 2015. Would personal carbon trading reduce travel emissions more effectively than a carbon tax? Transp. Res. Part D 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. Transp. Res. Part D 25–43.

Ricardo, 2021. Study on the taxation of the air transport sector (Final Report). Report for European Commission (DG TAXUD).

Rich, J., Lindhard, S., 2012. A long-distance travel demand model for Europe. Eur. J. Transp. Infrastruct. Res. 12, 1–20.

Schroten, A., 't Hoen, M., 2016. Road taxation and spending in the EU. CE Delf.

Sonnenschein, J., Smedby, N., 2019. Designing air ticket taxes for climate change mitigation: insights from a Swedish valuation study. Clim. Policy 19, 651–663.

statista, 2022. Distribution of travel and tourism spending in Europe in 2019 and 2021, by type.

The World Bank, 2022a. Population, total.

The World Bank, 2022b. Adjusted net national income per capita (annual % growth).

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

United Nations, 2022. The Paris Agreement, United Nations Framework Convention on Climate Change, UNFCCC.

van Geuns, M.F., 2021. Internalising the climate costs of European aviation (Master Thesis). CE Delft.

van Goeverden, C.D., 2009. Explaining Factors for Train Use in European Long-Distance Travel. Tour. Hosp. Plan. Dev. 21–37. https://doi.org/10.1080/14790530902847038

Volkswagen, 2022. T is for Tank-to-wheel (TTW), Newsroom E-mobility.

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

Wen, C.-H., Chen, P.-H., 2017. Passenger booking timing for low-cost airlines: A continuous logit approach. J. Air Transp. Manag. 64, 91–99.

Wikipedia, 2022a. Double auction.

Wikipedia, 2022b. Kiwi.com.

VIII. Appendix

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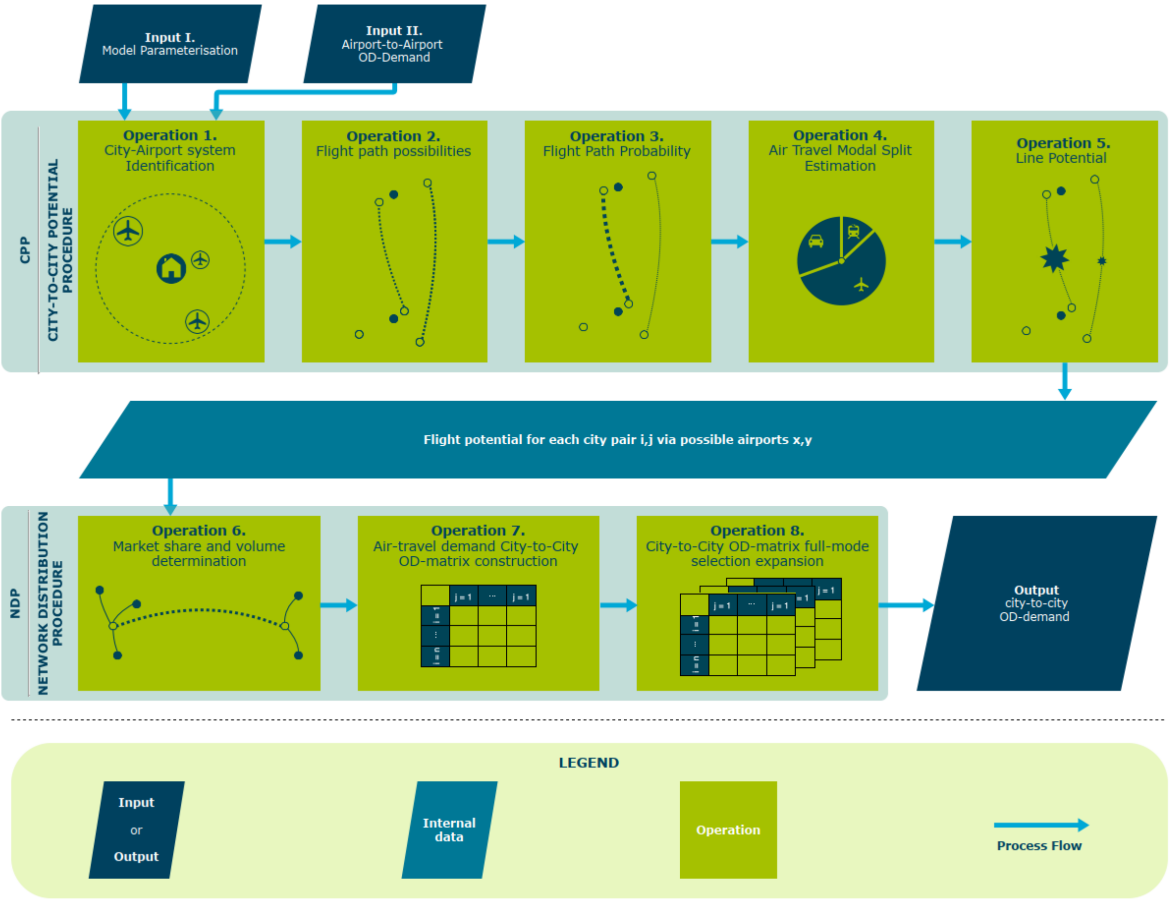
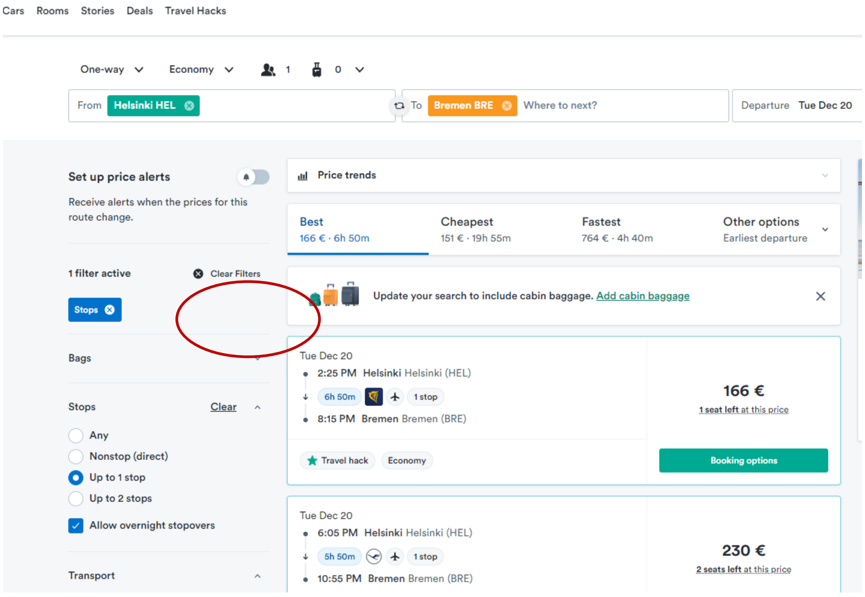
B Demand Estimation Methodology



Grolle (2020)

C Web Scraping



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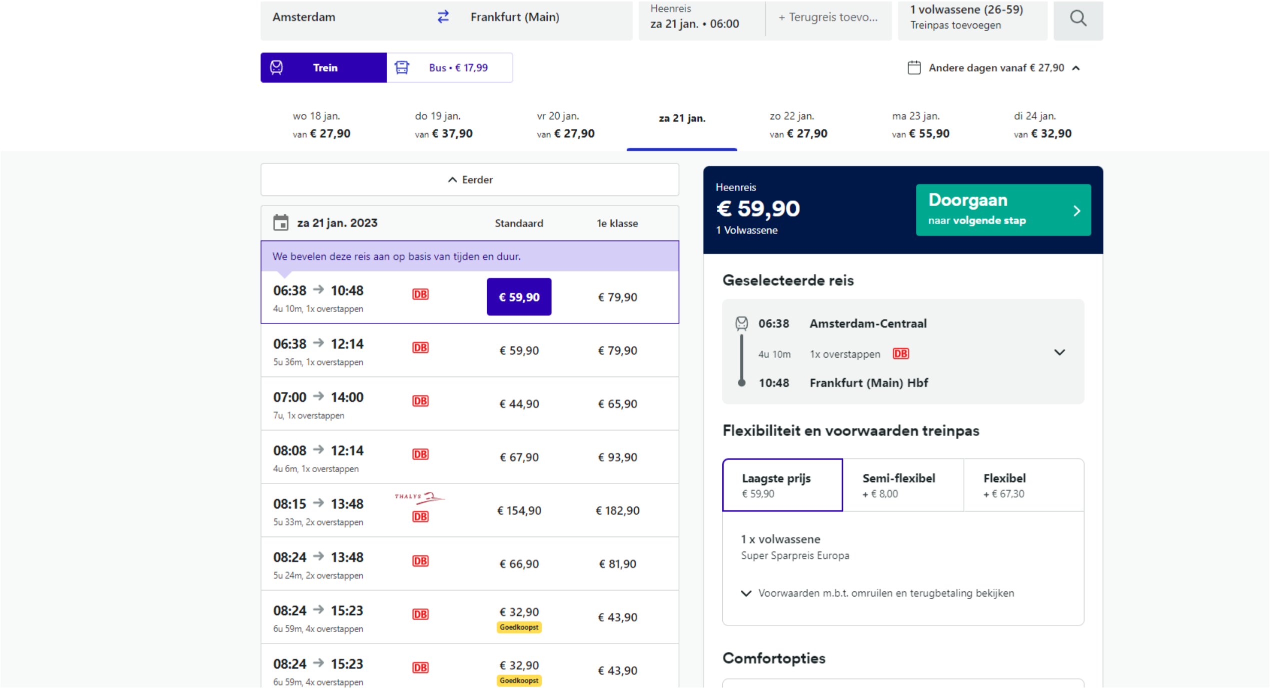

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We bevelen deze reis aan op basis van tijden en duur.

za 21 jan. 2023		Standaard	1e klasse
06:38 → 10:48 4u 10m, 1x overstappen	DB	€ 59,90	€ 79,90
06:38 → 12:14 5u 36m, 1x overstappen	DB	€ 59,90	€ 79,90
07:00 → 14:00 7u, 1x overstappen	DB	€ 44,90	€ 65,90
08:08 → 12:14 4u 6m, 1x overstappen	DB	€ 67,90	€ 93,90
08:15 → 13:48 5u 33m, 2x overstappen	THALYS DB	€ 154,90	€ 182,90
08:24 → 13:48 5u 24m, 2x overstappen	DB	€ 66,90	€ 81,90
08:24 → 15:23 6u 59m, 4x overstappen	DB	€ 32,90 Goedkoopst	€ 43,90
08:24 → 15:23 6u 59m, 4x overstappen	DB	€ 32,90 Goedkoopst	€ 43,90

Heenreis
€ 59,90
1 Volwassene

Geselecteerde reis

06:38 Amsterdam-Centraal
4u 10m 1x overstappen DB
10:48 Frankfurt (Main) Hbf

Flexibiliteit en voorwaarden treinpas

Laagste prijs	Semi-flexibel	Flexibel
€ 59,90	+ € 8,00	+ € 67,30

1 x volwassene
Super Sparpreis Europa

Voorwaarden m.b.t. omruilen en terugbetaling bekijken

Comfortopties

Trainline.com: Chromedriver extracting ticket price and travel time of first 8 connections

D Repository

Next to this report, the following files have been made available under 4TU (https://data.4tu.nl/portal/):

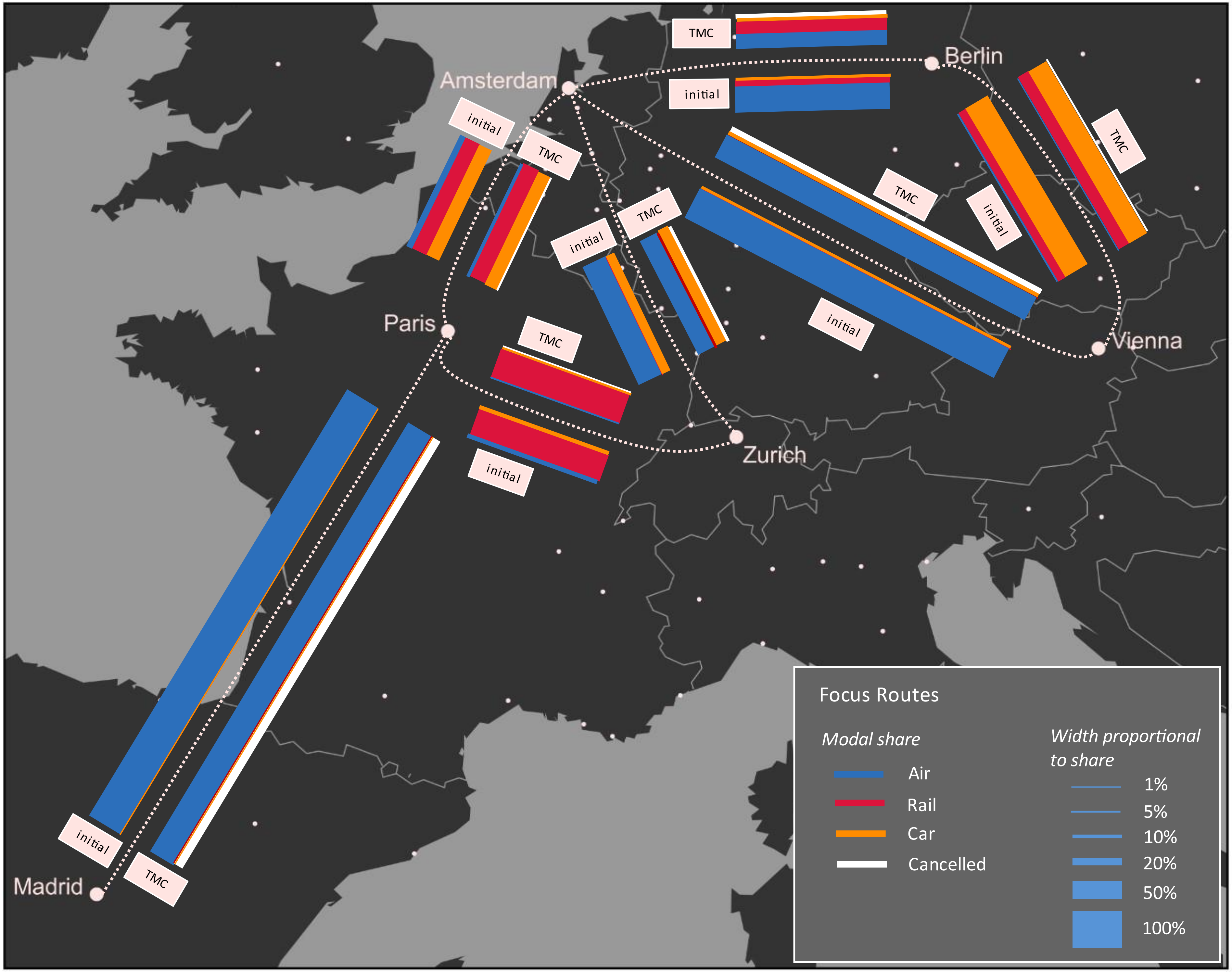
- ***Data_Collection_Air_and_Rail.xlsx***
  Flight and train ticket prices collected by web scraping (raw data)

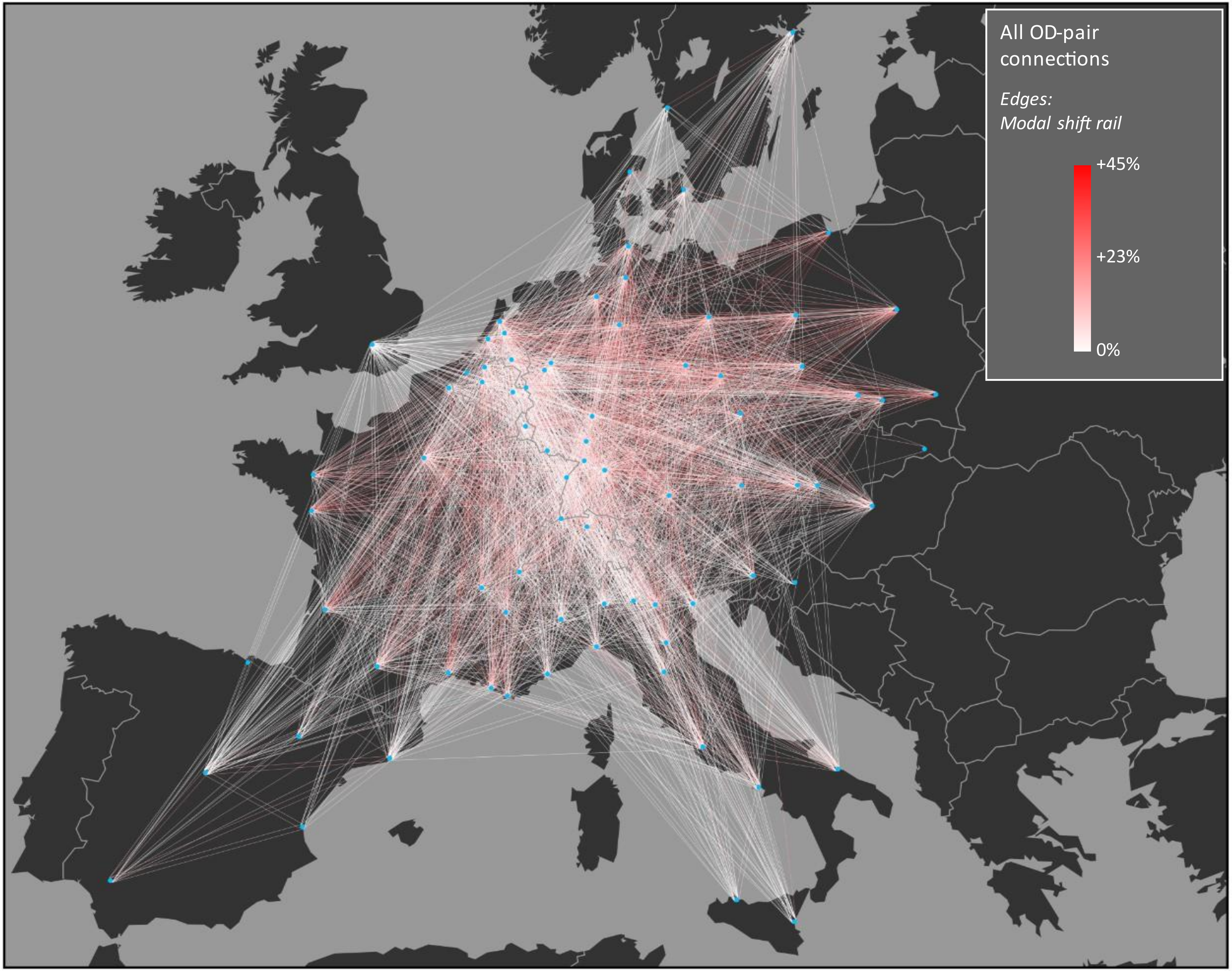
- ***TMC_Results_elastic_demand.xlsx***
  Output of the mode choice model, under elastic demand (trip cancellation included)

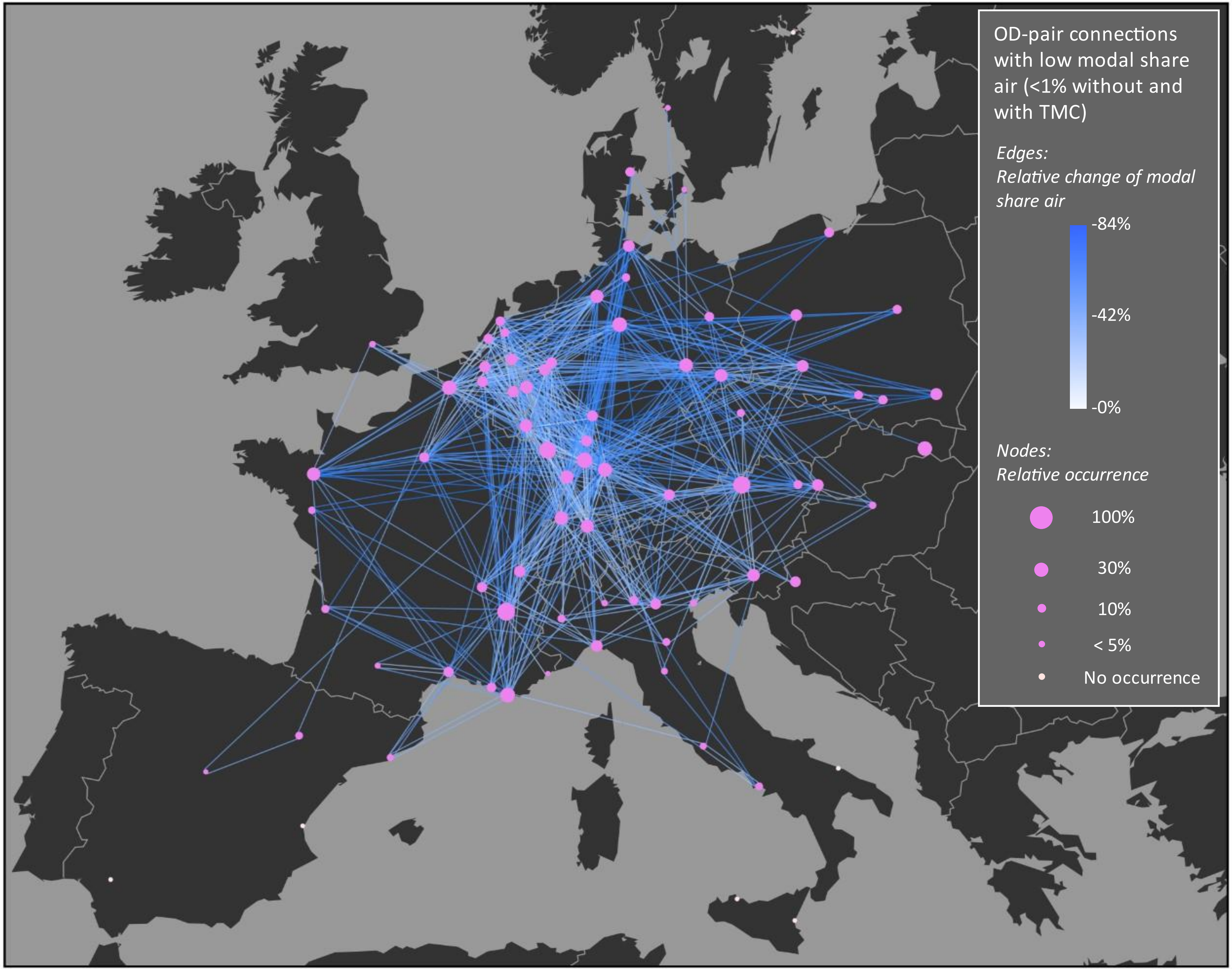
- ***TMC_Results_inelastic_demand.xlsx***
  Output of the mode choice model, under inelastic demand (trip cancellation not included)

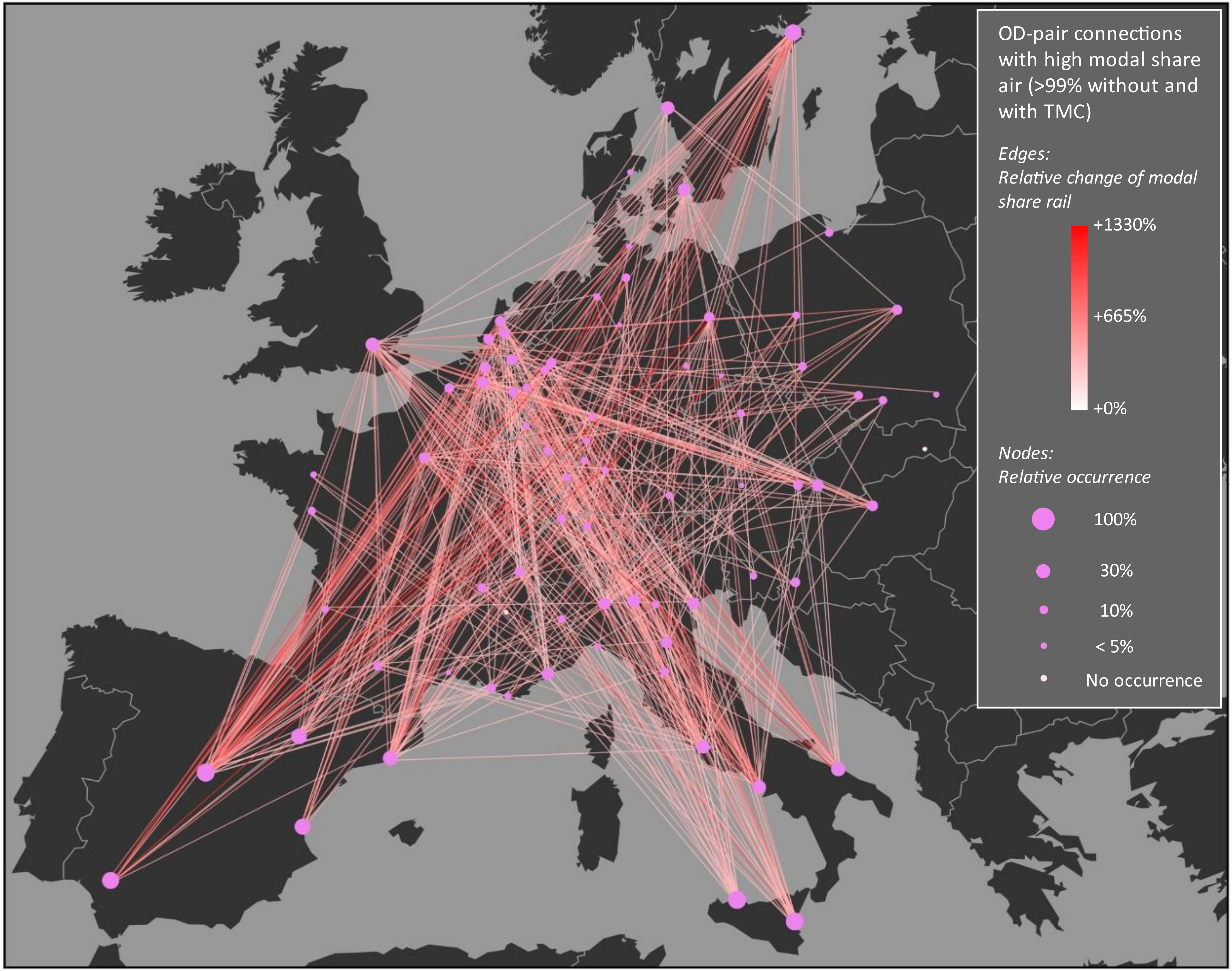
- ***TMC_Model_SandroTanner_30_01_2023.py***
  Python Mode Choice Model

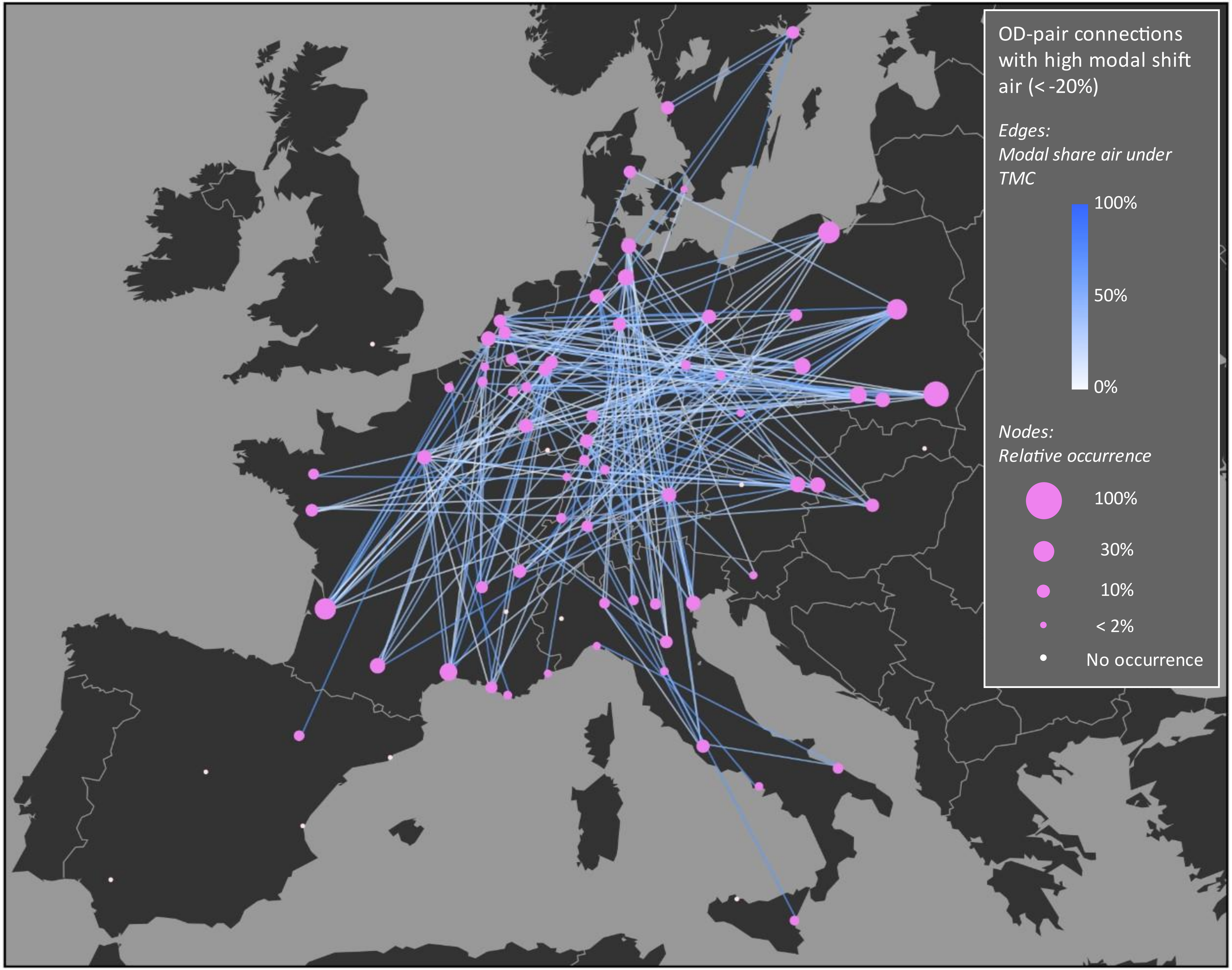
E Maps

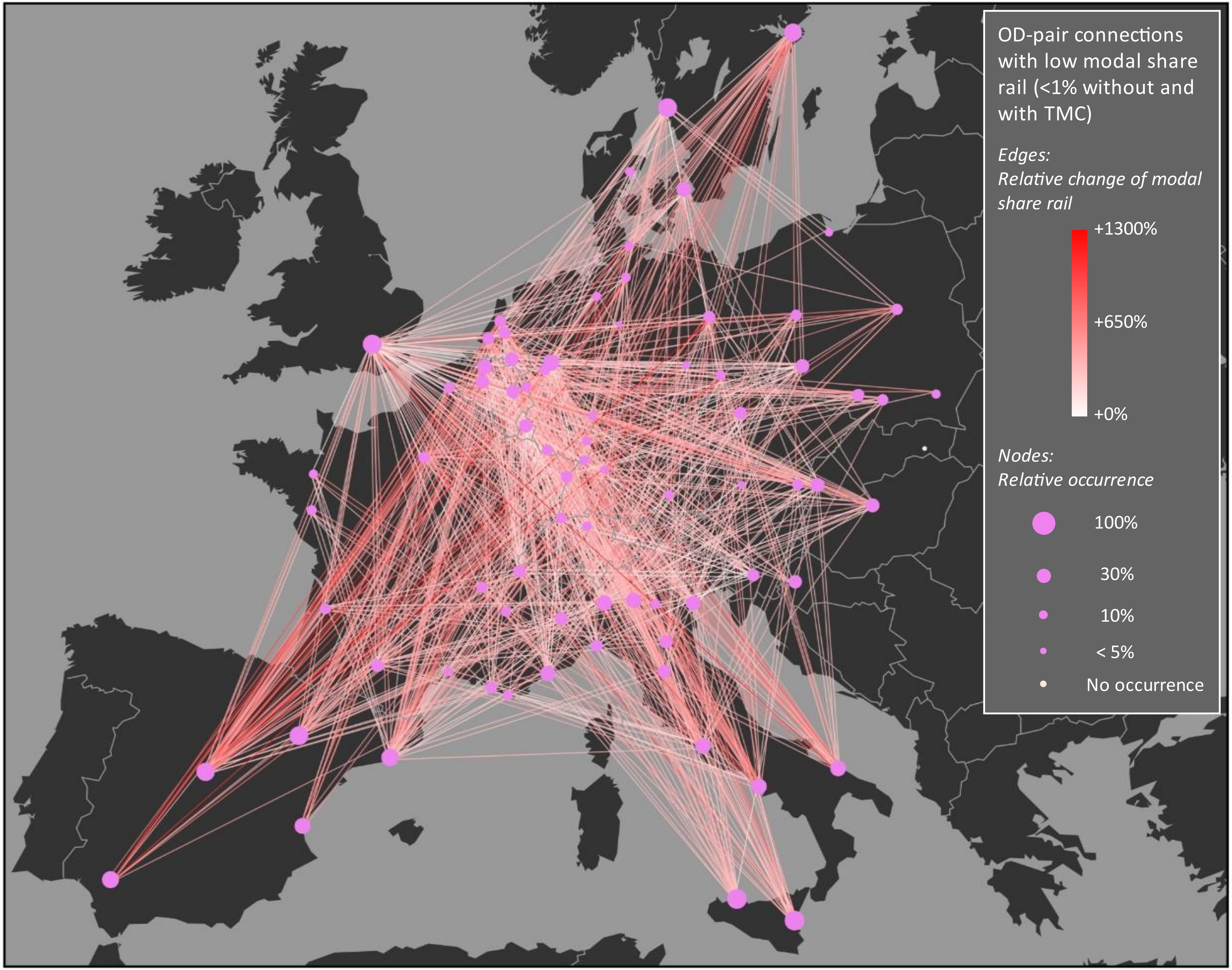

TMC
initial
Amsterdam
Berlin
Paris
Zurich
Vienna
Madrid
Focus Routes
Modal share
Air
Rail
Car
Cancelled
Width proportional to share
1%
5%
10%
20%
50%
100%

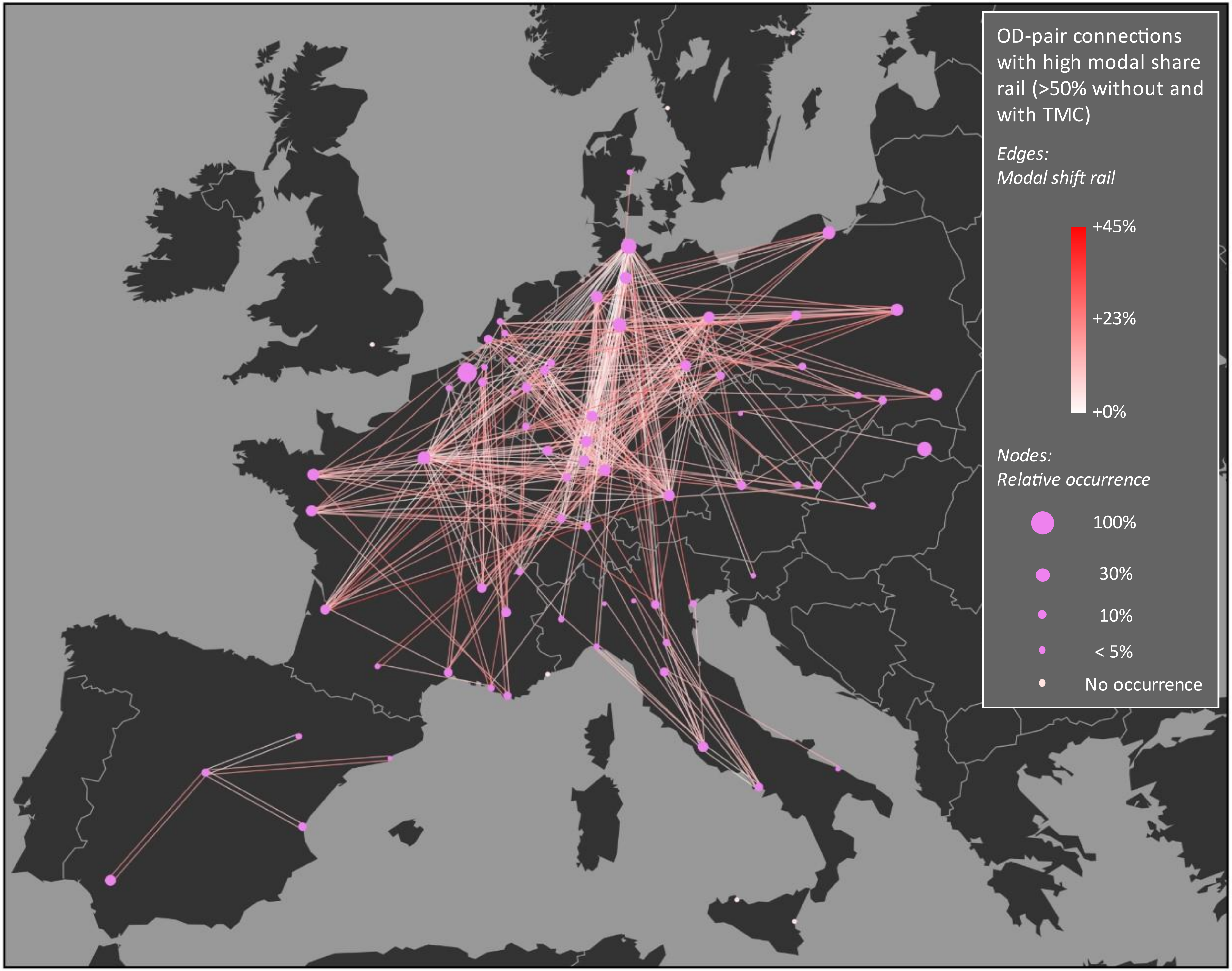

All OD-pair connections
Edges:
Modal shift rail
+45%
+23%
0%

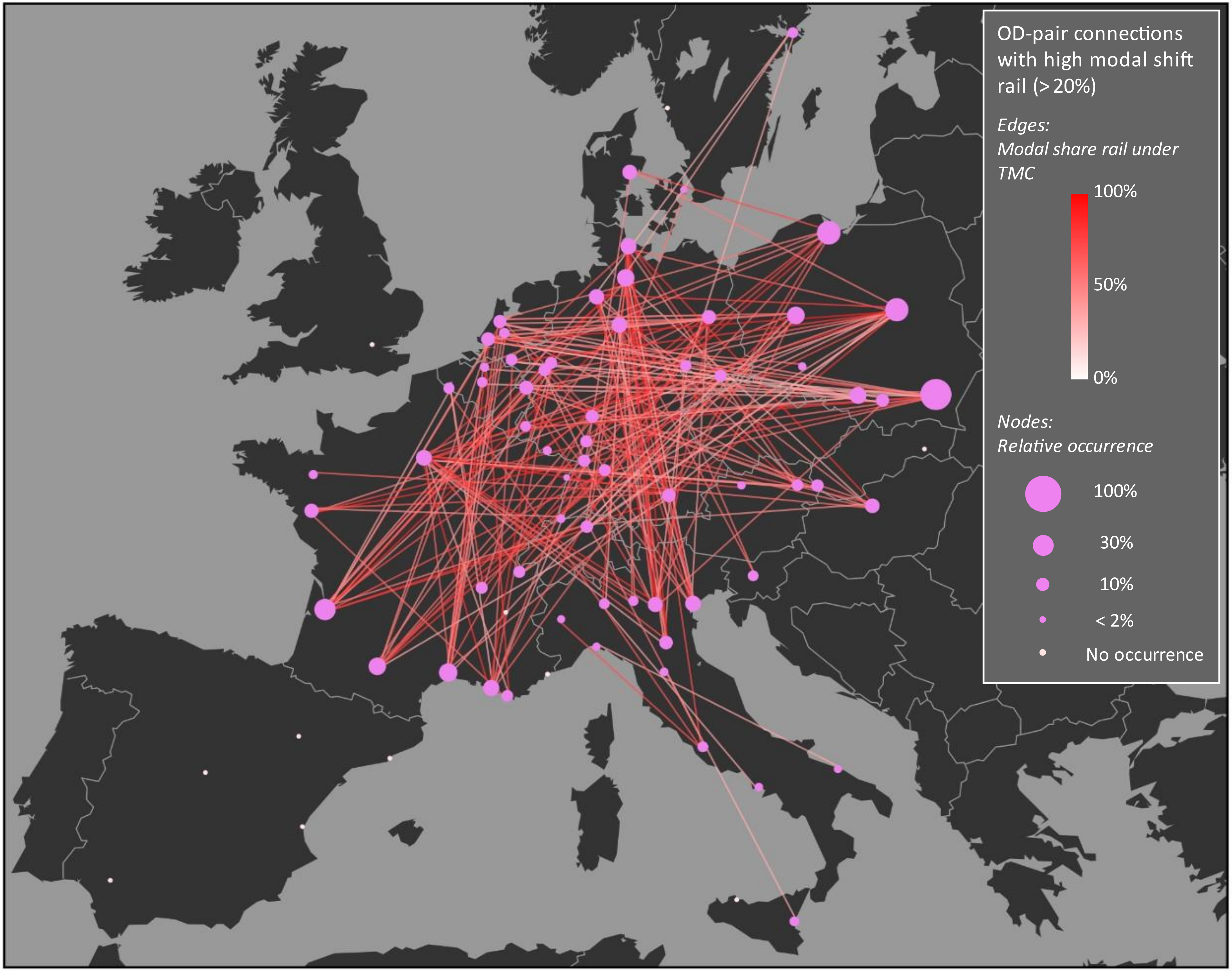

OD-pair connections with low modal share air (<1% without and with TMC)
Edges:
Relative change of modal share air
-84%
-42%
-0%
Nodes:
Relative occurrence
100%
30%
10%
< 5%
No occurrence

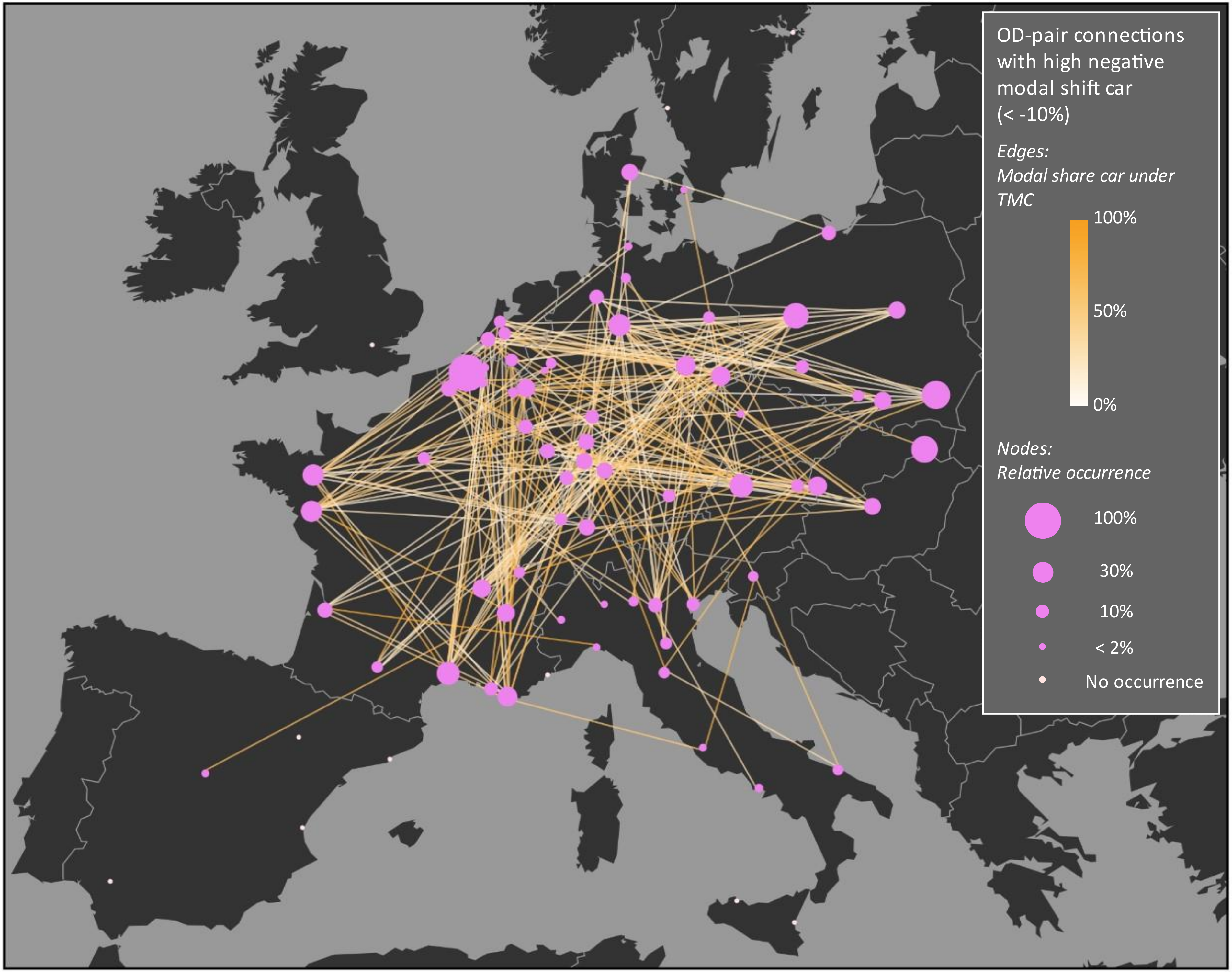

OD-pair connections with high modal share air (>99% without and with TMC)
Edges:
Relative change of modal share rail
+1330%
+665%
+0%
Nodes:
Relative occurrence
100%
30%
10%
< 5%
No occurrence

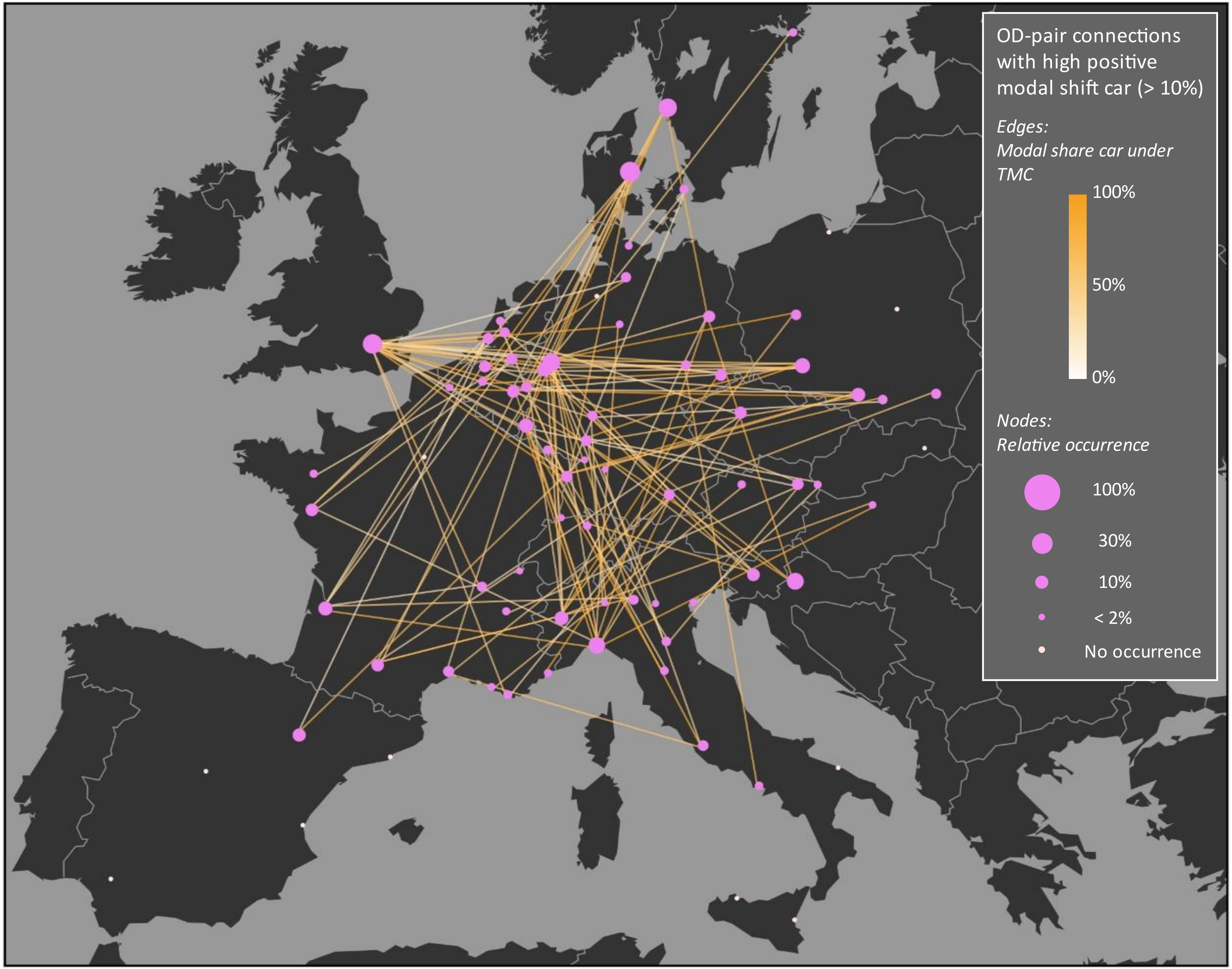

OD-pair connections with high modal shift air (< -20%)
Edges:
Modal share air under TMC
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence

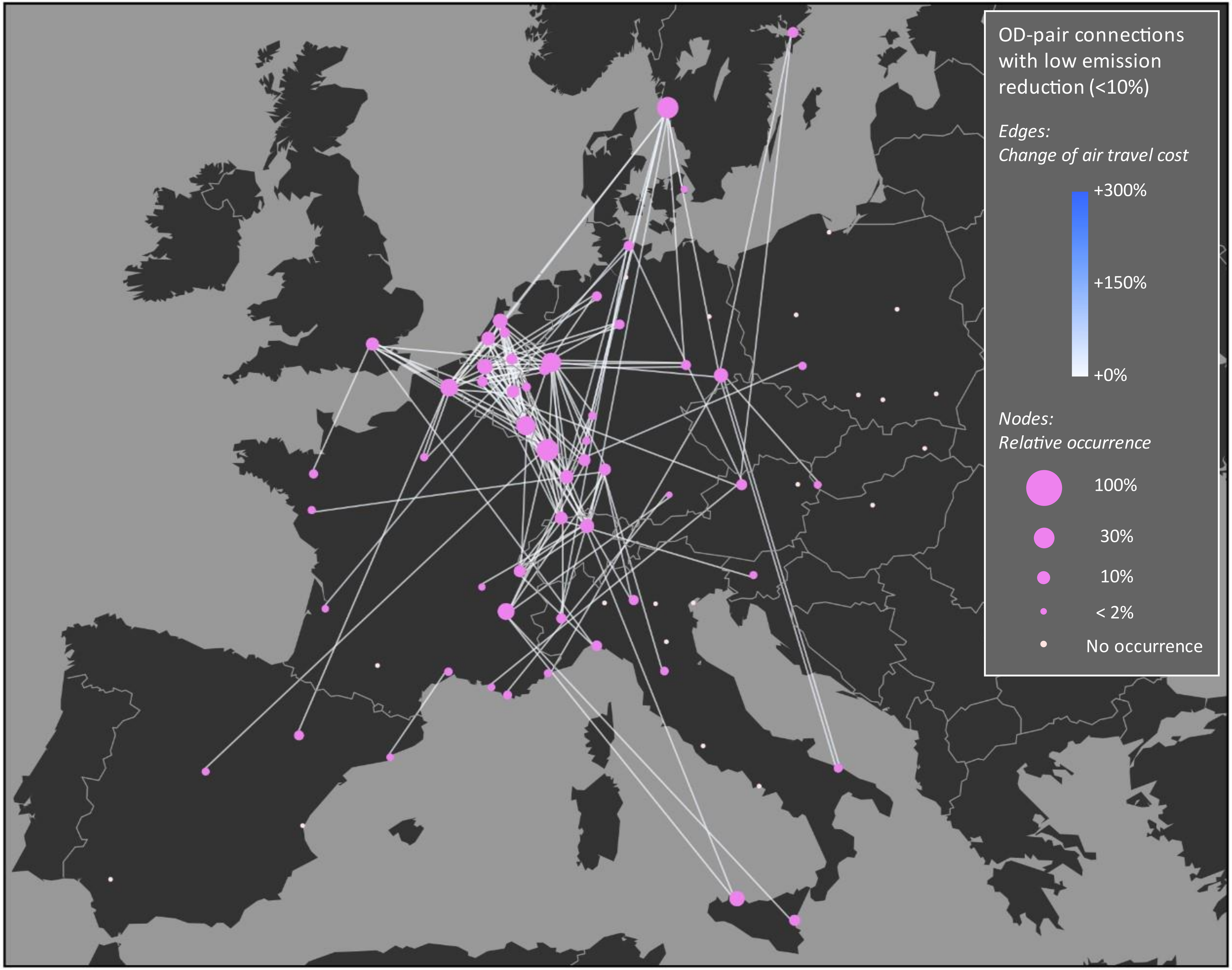

OD-pair connections with low modal share rail (<1% without and with TMC)
Edges:
Relative change of modal share rail
+1300%
+650%
+0%
Nodes:
Relative occurrence
100%
30%
10%
< 5%
No occurrence

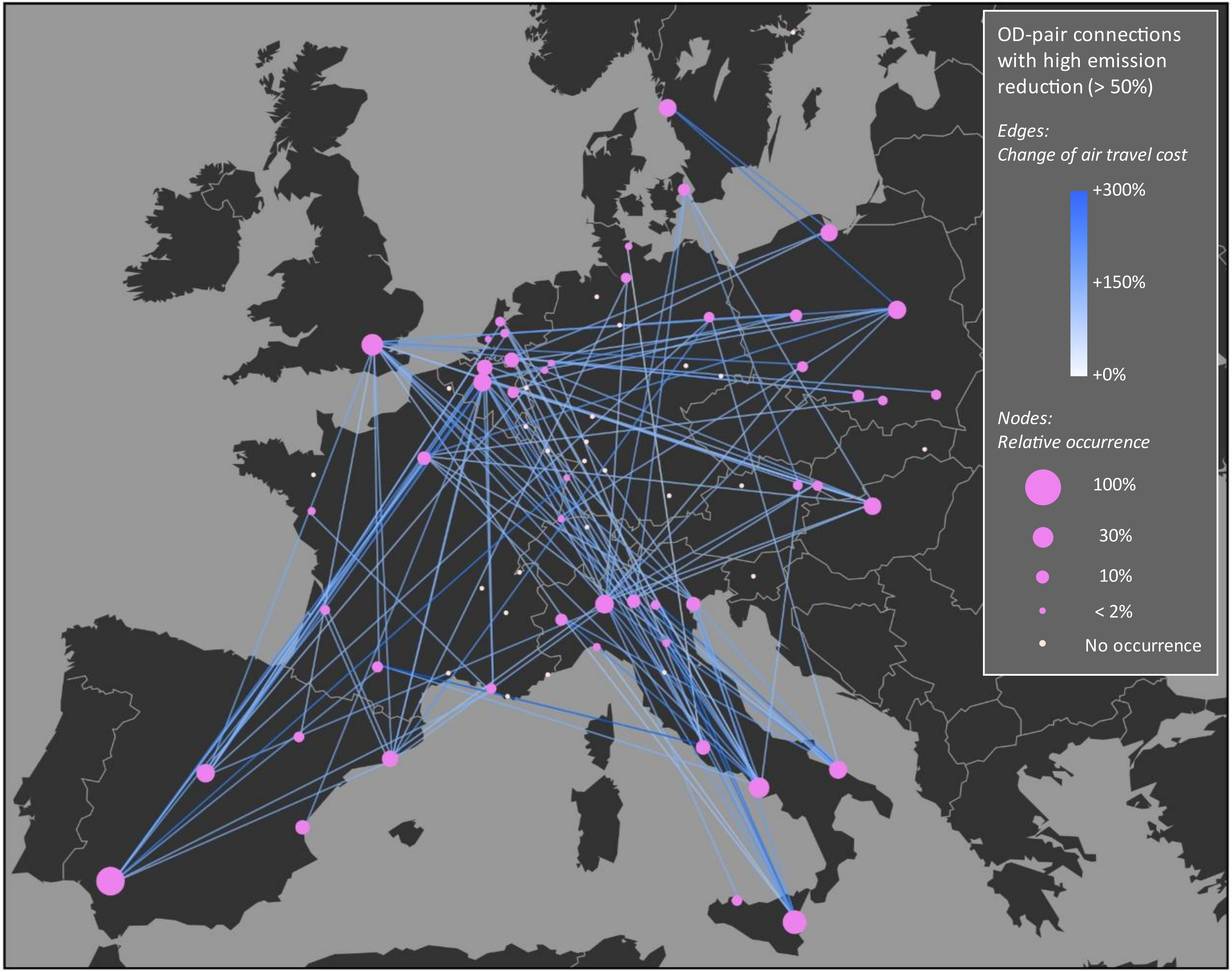

OD-pair connections with high modal share rail (>50% without and with TMC)
Edges:
Modal shift rail
+45%
+23%
+0%
Nodes:
Relative occurrence
100%
30%
10%
< 5%
No occurrence

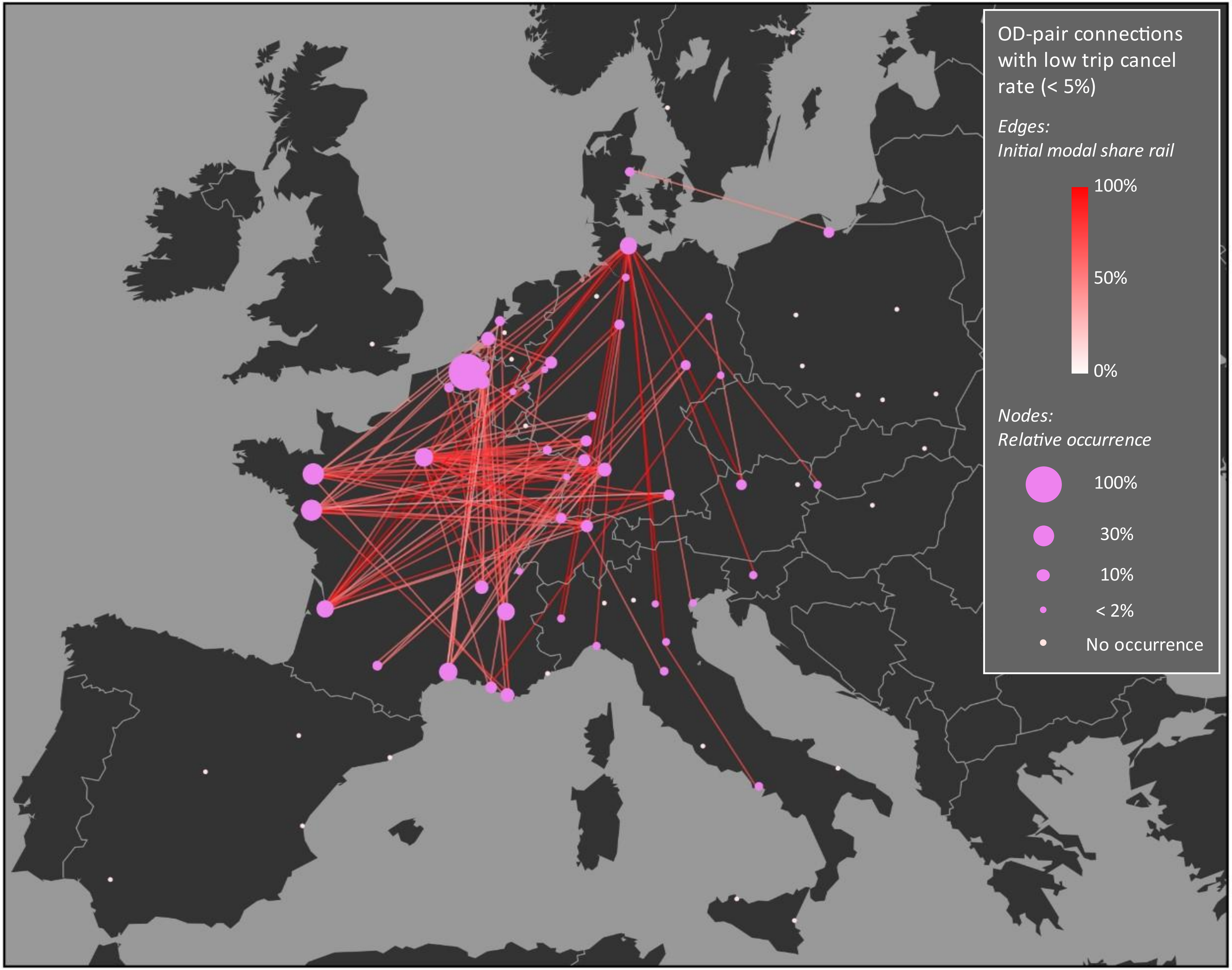

OD-pair connections with high modal shift rail (>20%)
Edges:
Modal share rail under TMC
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence

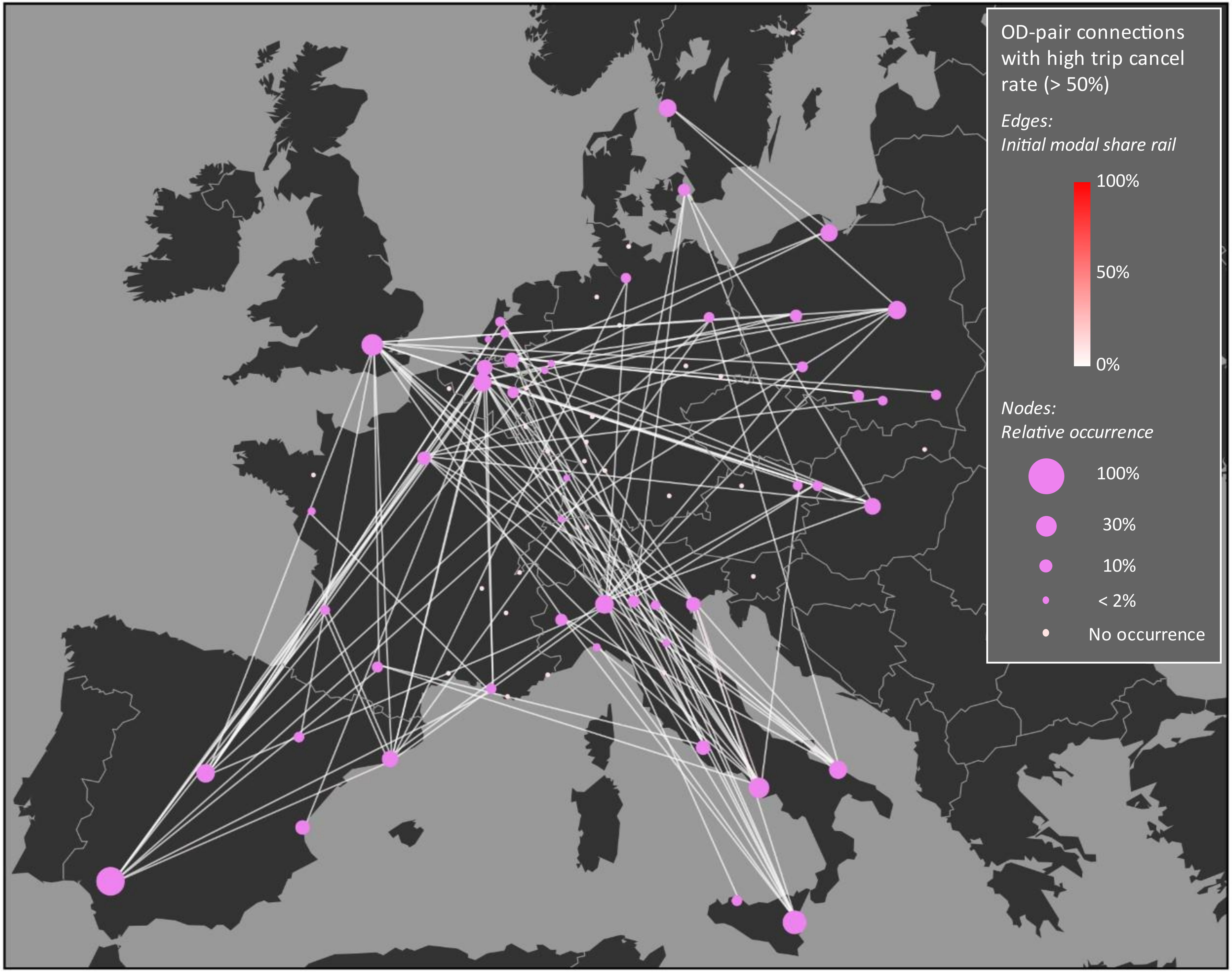

OD-pair connections with high negative modal shift car (< -10%)
Edges:
Modal share car under TMC
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence


OD-pair connections with high positive modal shift car (> 10%)
Edges:
Modal share car under TMC
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence


OD-pair connections with low emission reduction (<10%)
Edges:
Change of air travel cost
+300%
+150%
+0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence


OD-pair connections with high emission reduction (> 50%)
Edges:
Change of air travel cost
+300%
+150%
+0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence


OD-pair connections with low trip cancel rate (< 5%)
Edges:
Initial modal share rail
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence


OD-pair connections with high trip cancel rate (> 50%)
Edges:
Initial modal share rail
100%
50%
0%
Nodes:
Relative occurrence
100%
30%
10%
< 2%
No occurrence