# The impact of a ban on short-haul flights on transfer passengers and CO2 emissions

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| Project Duration: | 08, 2024 - 05, 2025 |
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# Preface

In front of you is my thesis, my final work in my career as a student. My interest in transport and mobility has always fascinated me, particularly the aviation sector and its role in society. I believe that with proper Air-Rail integration, we can help preserve airports and air traffic while reducing unnecessary flights. This approach can contribute to lower carbon emissions without sacrificing the efficiency of our transport system. From this conviction, I decided to research Air-Rail integration. While studying the literature, I encountered the proposal to ban short-haul flights. This topic intrigued me because it is both significant and promising in the pursuit of lower carbon emissions. Consequently, I decided to explore it further, resulting in this research.

In this preface, I would also like to thank my committee. First, I would like to express my gratitude to Barth Donners for his guidance and valuable discussions on my thesis content. His support greatly advanced my research. I also wish to thank Jorik Grolle for stepping in as supervisor during Barth's holiday. My appreciation extends to Royal HaskoningDHV for the opportunity to complete my thesis at their company. Finally, I would like to thank my supervisors at TU Delft, Oded Cats and Jan Anne Annema. Their assistance, particularly in writing, was sometimes necessary but also very instructive. Additionally, I would like to thank Editgpt for ensuring this report is grammatically correct and readable for those interested in my thesis.

*Bart Schermer*
*Delft, May 2025*

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# 1 Introduction

In recent years, the concept of environmental damage has gained significant prominence within society. Following the signing of the environmental agreement in Paris, the European Union has been actively developing legislation to reduce CO2 emissions across various sectors, including the transport sector.

In the context of long-distance travel, it is evident that the predominant mode of transportation is by planes. The high frequency of flights, coupled with the considerable energy requirements associated with aviation, contributes to a substantial environmental footprint within this market. As a result, the European Union aims to implement legislation in this sector designed to mitigate the environmental impact. One goal of this policy is to reduce the number of passengers travelling by air.

The issue is that aviation drives prosperity. According to a study by Volkhausen (2022), an airport in a region provides an economic boost of 2-6%. Implementing policies that reduce air travel could diminish or eliminate this economic benefit. Furthermore, an airport ensures good accessibility for an area, as noted by Sun et al. (2024). A decline in passenger numbers may jeopardise an airport's viability, potentially leading to its closure. Therefore, any policy implemented must consider these factors, ensuring that while CO2 emissions are reduced, the economy does not suffer significantly.

A potential solution to this issue could involve promoting stronger cooperation between air and rail transport (Givoni & Banister (2006)). In such a system, airlines could focus on long-haul flights exceeding 1,500 kilometres, while high-speed rail (HSR) in optimal form could take over shorter journeys. This division of responsibilities would optimise transportation modes and reduce environmental impact, as HSR is at this moment a faster option than planes for distances up to 750 km (Adler et al. (2010)). According to research by Roman & Martin (2014), this is crucial because an alternative can only compete effectively with planes if it can cover a distance as quickly, or nearly as quickly.

Research by Givoni & Banister (2006) highlights HSR as a viable alternative to short-haul feeder flights due to its significantly lower CO2 emissions (Prussi & Laura (2018)). Additionally, HSR can expand the service area of airports by offering seamless ground connections to surrounding regions (Wang et al. (2020)). The result of this collaboration is that an airport can continue to transport passengers. An additional advantage is that when an airport has an HSR station, its service area expands. This can therefore compensate for the share of passengers that aviation loses due to the introduction of the HSR.

At this very moment there are already examples of collaboration between air and rail operators, such as the partnership between Lufthansa and Deutsche Bahn, which aims to transfer more passengers to rail services (De Boer (2022)). However, as Xia & Zhang (2017) notes, there is still competition between planes and HSR on overlapping routes, and airlines continue to operate flights on corridors already served by HSR. This competition undermines the benefits of collaboration and underscores the need for more integrated strategies.

To encourage more people to choose HSR or an Air-Rail alternative, the European Union could consider introducing a ban on short-haul flights. This would give HSR a monopoly until a passenger exceeds the ban. As a result, more people would, in theory, use the train instead of the plane, potentially leading to a reduction in CO2 emissions from the transport market.

To understand how the ban on short-haul flights would work, it is important first to define what constitutes a short-haul flight and to examine the potential significant impact on the market. There are three types of flights, categorised as short-haul, medium-haul, and long-haul. Each type of flight has its own minimum and maximum distance it must travel before it can be categorised as that type of flight; these distances are listed in Table 1.1.

A short-haul flight is characterised as a flight that operates over a maximum distance of 1,500 kilometres (Dobravsky (2021)) before reaching its destination. Typically, these flights are conducted by smaller aircraft that can accommodate up to 100 passengers. Which indicates that these airplanes are mostly small type of planes. These types of flights are primarily used by low-cost carriers and regional airlines. They are also an essential part of the hub-and-spoke network, transporting passengers on short journeys to major hubs, where they can transfer to medium- or long-haul flights.

| Minimum distance (km) | Maximum distance (km) | Type of flight |
|---|---|---|
| 0 | 1500 | Short-haul flight |
| 1500 | 4500 | Medium-haul flight |
| 4500 | ∞ | Long-haul flight |

**Table 1.1:** Types of flights for different distances

Major hubs around Europe have a significant proportion of their flights classified as short-haul. Figure 1.1 shows that the major airports in Europe have between 30% and 40% of short-haul flights. Figure 1.2 illustrates that the aviation market in Europe consists of 74.2% short-haul flights. As shown in the tables, short-haul flights play a significant role in the aviation sector.

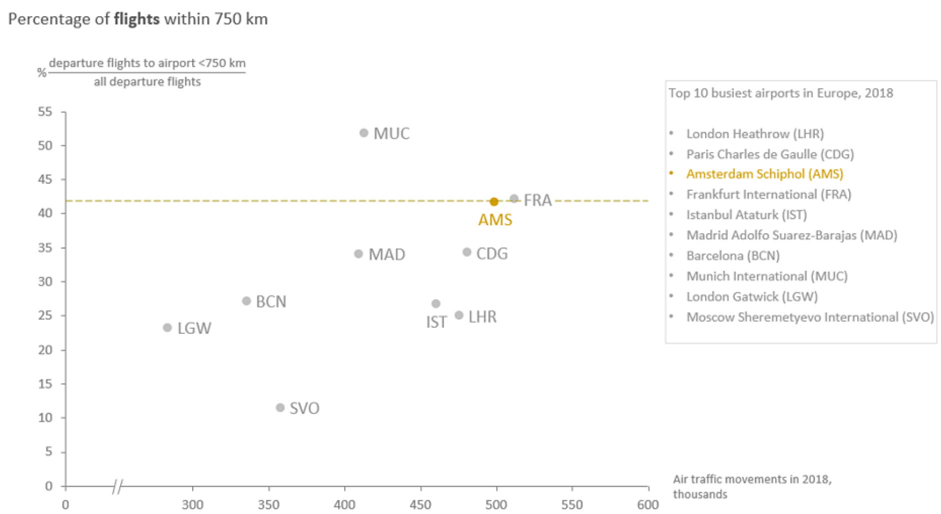


**Figure 1.1:** Impact of flights within a range of 750km on various airports arround Europe (Pijnappels (2020))

But what impact do short-haul flights have on CO2 emissions in Europe? Figure 1.2 illustrates that 74.2% of total flights are responsible for 24.9% of all emissions from aircraft in Europe. This suggests that if a complete ban on short-haul flights were implemented, 74.2% of all flights within Europe would be banned, theoretically reducing CO2 emissions from aviation by 24.9%.

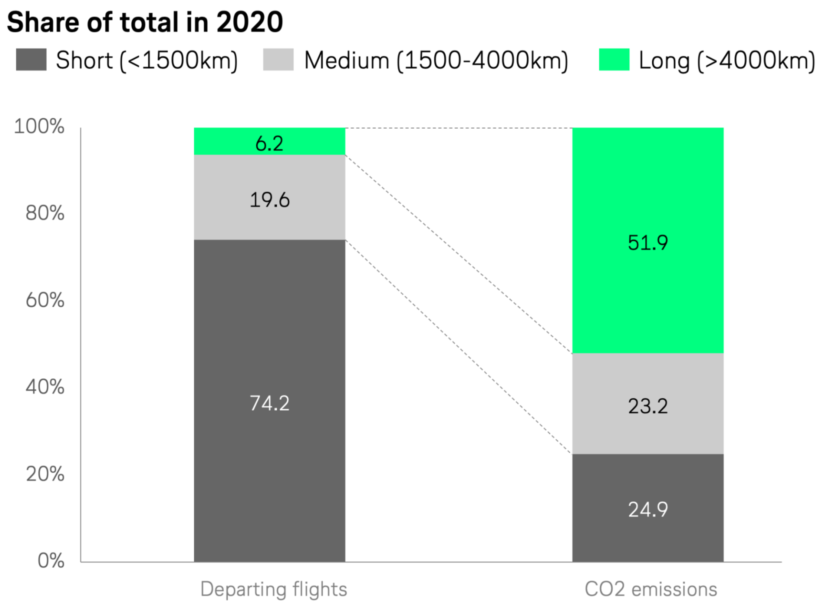


**Figure 1.2:** CO2 Short vs Medium vs Long distace flights (Dobravsky (2021))

To check whether a ban on short-haul flights results in a 24.9% reduction, existing literature was examined to confirm this fact. Previous research by Baumeister & Leung (2020) found that an earlier study in Finland reported a 95% reduction in CO2 emissions due to a ban on short-haul flights. However, this study primarily focused on the aviation market in Finland, which consists mainly of domestic flights and has few transfer passengers. Additionally, the only viable alternative was the national train company. Nonetheless, this study indicates that the ban could have a significant impact on national markets.

A more Europe-oriented study conducted by Avogadro et al. (2021) examined the implementation of a ban that prioritises passenger considerations. This implies that only flights that do not impede passenger travel time will be prohibited. The findings indicated that only 3.02% of the seats would be cancelled, with the majority of these cancellations occurring in France. This study shows that the impact of the ban would be smaller than expected.

The study by de Bortoli & Féraille (2024) investigated how a ban would affect a specific route, selecting the Paris-Bordeaux route for analysis. The study found that, under a business-as-usual trip substitution scenario, high-speed rail (HSR) achieves net zero emissions after 60 years. This means the emissions from the HSR can offset those of the aircraft after 60 years. This is because the construction of HSR infrastructure will also involve ecological damage. When a ban on short-haul flights is implemented, this time frame could be reduced to 10 years.

So to reduce CO2 emissions from the aviation sector, cooperation between aviation and rail may be beneficial, according to Givoni & Banister (2006). This is because rail's CO2 emissions are lower than those of aircraft, as noted by Prussi & Laura (2018). The challenge is that HSR trains are being built on routes also served by aircraft. This creates competition, which, according to Xia & Zhang (2017), prevents the achievement of the desired goals. To encourage rail transport among passengers, a ban on short-haul flights could be implemented. According to the studies by Baumeister & Leung (2020) and de Bortoli & Féraille (2024), this should lead to an increase in passenger numbers on train networks. However, these studies cannot confirm the 24.9% reduction in CO2 emissions when a ban on short-haul flights is implemented across Europe.

The problem with this ban is that much remains unknown about its actual impact on short-haul flights when implemented across Europe. Indeed, Baumeister & Leung (2020) study provides some insights, but it focuses only on the domestic market, where almost all flights can be considered short-haul. With many passengers wanting to travel directly and the removal of the flight option, it is expected that many will opt for the train, resulting in a significant reduction in CO2 emissions. What the current studies lack is information on the effect of transfer flights on the effectiveness of this ban accross the whole of Europe. Are passengers willing to take the train, or do they prefer to continue flying around the ban and are they willing to travel longer distances to do so? How will these transfer passengers influence the effectiveness of this policy? The studies by Baumeister & Leung (2020) and de Bortoli & Féraille (2024) only focus on small routes where these transfer passengers do not often occur. Thus, the role of these transfer passengers is not explained in the literature, and there is no literature that explains the effects of the ban on Air-Rail usage. Additionally, no literature was found on the redistribution of passengers across hubs. Will European hubs continue to receive enough passengers to remain viable, and how will a ban on short-haul flights affect passenger flows across Europe?

This research focuses on passengers' route choices at the time Europe implements a ban on short-haul flights. It assumes that when the ban is implemented, the EU already has a well-functioning high-speed rail (HSR) network. By assessing passengers' route choices, this study examines the impact of the ban on CO2 emissions from aviation, including the role of transfer passengers. Additionally, it explores the effect of the ban on the use of the Air-Rail network and its impact on various hubs across Europe. This will be done using the research questions outlined in Table 1.2.

| **How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?** |
|---|
| Sub-questions |
| 1. How can a ban on short-haul flights be designed, and what indicators could affect its impact? |
| 2. How can a base scenario be developed to research the effects of the ban on short-haul flights? |
| 3. How will passenger mode choice affect CO2 emissions in the aviation sector for each type of ban on short-haul flights? |
| 4. Does the ban on short-haul flights promote the use of the Air-Rail network? |
| 5. How will a ban on short-haul flights change the competitive position of hubs across Europe? |

**Table 1.2:** Research question and Sub-questions

This research report comprises several chapters, each covering a specific aspect of the research. First, chapter 2 will examine the ban on short-haul flights, clarifying what the ban entails and how it will affect transfer passengers. It will also outline the aspects investigated in this study. Chapter 3 will explain and illustrate the methodology employed. This will be followed in chapter 4 with an overview of the different parameters used in the method. Then, chapter 5 will carry out verification and validation to assess the model's performance. Finally, chapter 6 will present the results of the algorithm, leading to the conclusions drawn in chapter 7.

# 2 Conceptual Design of a Ban on Short-Haul Flights

This chapter will examine the implications of the ban on short-haul flights and its effects. It will begin by outlining the current state of the transport market, followed by a description of the ban's design. Then, the various problems associated with the ban's design will be addressed, followed by an explanation how these aspects will influence the effectiveness of the ban. Finally, this chapter will discuss the indicators used in this research to prove different aspects of the ban.

## 2.1. Current state

Before the current state can be assessed, it is necessary to look at the different terms used in the transport market. These terms are important to understand what the impact will change and how this will effect different other indicators. The two terms to be discussed are transfer passengers and hubs.

### 2.1.1. The origins of transfer passengers and why they use hubs

In the aviation market, there are two ways to travel towards a final destination. Before the current state can be explained in detail, it is important to understand the difference. The two ways of travel result in the following type of passengers, there are direct passengers and transfer passengers. The different types of passengers result from the strategies employed by various airlines. Some operators focus on affordable travel and primarily concentrate on direct routes, using a strategy called point-to-point travel. Other operators focus on transporting passengers to a central hub, from where they can transfer to their final destination. This strategy is called the hub-and-spoke network.

To expand an airline's service area, airlines use a hub-and-spoke network. The idea behind the hub-and-spoke network is that passengers with different final destinations are taken by a large aircraft to a particular hub. Once they arrive at the hub, passengers can transfer to another flight, which takes them to their final destination. Major airlines provide this service to passengers by using regional flights called feeders. These feeders bring passengers to the central hubs, where they can transfer to intercontinental flights. Using this technique helps airlines fill their planes, enabling them to operate with a high load factor. An example of the hub-and-spoke network versus the point-to-point network is shown in Figure 2.1

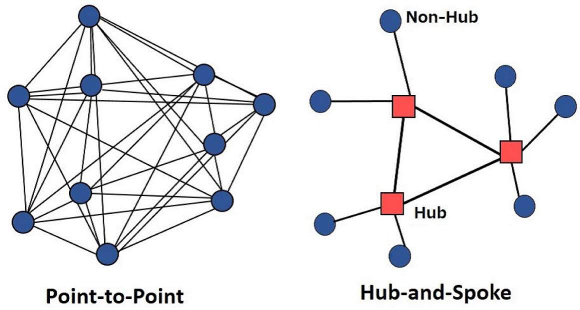


**Figure 2.1:** Point to point en hub and spoke design (Kuroki & Matsui (2024))

The idea behind the hub-and-spoke network is that a central hub gathers passengers for transport on larger modes of transport. The advantage of this method is that there are significantly fewer routes to be served by a specific carrier, as shown in Figure 2.1. This expands the service area for carriers without requiring more routes. The downside is that passengers travel less directly to their final destination, resulting in higher average CO2 emissions per individual passenger compared to direct travel.

The hub-and-spoke network consists of two types of airports. The first type comprises regional airports; the second type consists of hub airports. These hubs are the most relevant airports for companies employing the hub-and-spoke strategy. Hubs also play an important role in their regions. Having a hub can greatly enhance accessibility to the area. Additionally, hubs are often large airports that provide significant economic benefits to the region. To identify a hub, two key characteristics should be noted. The first characteristic of a hub is that it serves as the home base for a large carrier. For example, Schiphol (Amsterdam) is the home base of KLM, while Lufthansa is based in Frankfurt and Munich. Both carriers also employ the hub-and-spoke strategy.
The second characteristic is that the hub must have a strong connection to the world. As explained above, one advantage of using a hub-and-spoke network is that connectivity is significantly enhanced. This ensures that large hubs can be recognized by their level of connectivity.

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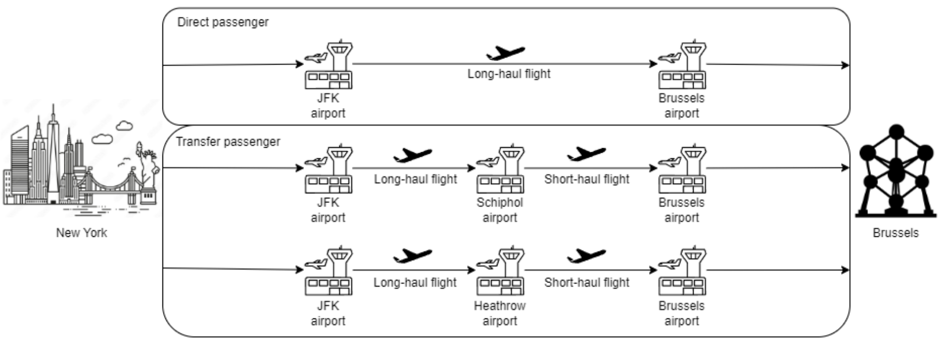



**Figure 2.2:** Three options for a passenger to travel between New York and Brussels

In this example, there are three possible routes a passenger can choose. The first option is a direct flight from New York to Brussels, which is a long-haul flight. The other two options involve transfers. In the first of these, the passenger takes a long-haul flight to Schiphol Airport and then transfers to a short-haul flight to reach the final destination. The last option is a long-haul flight to Heathrow in London, followed by a transfer to a short-haul flight to Brussels.

## 2.2. Conceptual design

The previous section explained the current network. As shown in Figure 2.2, passenger options mainly consist of flight choices. Implementing the ban on short-haul flights should alter this scenario. This section will discuss the details of this ban.

A ban on short-haul flights can be implemented in several ways. This research has chosen to examine two types of bans on short-haul flights. The first is based on the minimum distance a flight must cover before it can operate and is called a distance based ban. The second option is more complex and will consider alternatives before implementing a ban; this is referred to as a time-based ban. Figure 2.3 illustrates a small example of how this ban is structured and which factors must be considered.

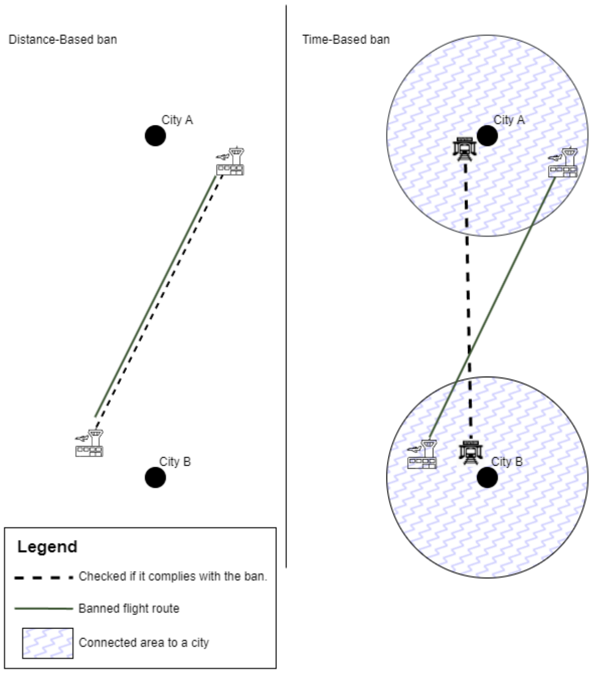



**Figure 2.3:** A simplified overview of difference between the two types of bans on short-haul flights

### 2.2.1. Distance based ban

The distance-based ban will assess the distance between two airports. If this distance falls below the ban threshold, the flight will be prohibited. This approach will ensure simplicity for implementers, as carriers can easily calculate the ban.

The advantages of the ban primarily lie in the simplicity of the policy. Indeed, it can be implemented very easily. However, this simplicity also presents a significant disadvantage; the best solution for each individual scenario may not be considered. For instance, when a flight affected by the ban travels over mountains that cannot be crossed by other modes of transport, it will result in a complete lack of transportation between those two cities.

The ban on short-haul flights could promote two possible consequences. The first is that this ban will increase the investment in alternative transport. For instance, the HSR network may be expanded, or more tunnels constructed. Ultimately, countries want their cities to remain easily accessible. However, the downside is that countries with good alternative connections or those less affected by natural barriers need to invest significantly less money in possible alternatives. This can create unfairness among the member states of the European Union.

The second major consequence of the ban is that passengers who must travel between two cities, where no alternative transport is available, will be forced to detour. As a result, the travel time for these passengers will increase significantly, and leading to higher average $CO2$ emissions due to longer flights. Ultimately, this creates a negative impact for both passengers and the European Union.

### 2.2.2. Time based ban

The ban based on distance has several advantages and disadvantages. To compensate for the simplicity that causes cities' accessibility to decrease, it was chosen to design a ban based on time as well.

This approach evaluates trains as a viable alternative. If a passenger can reach the other city within the time frame using high-speed rail, the flight between the two cities will be banned.

The first step in designing this ban is to calculate travel times between two cities based solely on HSR travel. When the travel time between two cities falls within the limits of the ban, it considers which airports are connected to these cities. This is important because airports are typically not located in the city centre. Thus, all airports within Europe can be linked to a city and be included in the ban. A circle with a radius of 50 km is drawn around each city, and all airports within this radius are considered connected. If the travel time by HSR between two cities is within the limits of the ban. The routes between the associated airports will de banned.

The advantage of this ban is that potential alternatives will be considered on a case-by-case basis. This leads to more targeted policies, preventing passengers from having to detour. When these passengers have to detour, the availability of alternatives means there are plenty of other options available. Also this form of ban is able to better account for natural barriers such as mountains or the sea.

A major drawback of this ban is its complexity, particularly concerning who is responsible for checking whether a route falls under the ban. This complexity increases the likelihood of errors by those implementing the policy. Furthermore, this method does not promote innovation; if a city has poor connections to other cities via high-speed rail (HSR), it may continue to operate more flights instead. As a result, cities may find it more advantageous not to invest in new HSR lines to avoid losing additional routes from their airports, thereby maintaining their airports' strong position.

## 2.3. Aspects affecting the effectiveness of the ban

In designing the ban, there are already several aspects that can influence its effectiveness. First, the European Union cannot impose laws in all European countries. Another factor is the availability of alternatives for passengers. It is crucial for passengers to have options aside from short-haul flights if their flight is canceled due to the ban. Lastly, passengers traveling beyond the ban's scope must access the Air-Rail network to enhance the ban's effectiveness and maintain the hub-and-spoke network. This section will address these factors and their impact on the ban's effectiveness.

### 2.3.1. The impact of Non European Union members

Not all the countries in Europe are part of the European Union. This causes problems with legislation, as the ban on short-haul flights will only apply to countries that are members of the European Union. This is due to regulations concerning air traffic between countries. As a result, the EU cannot ban flights to countries that do not fall under EU law, however there are exceptions. These non-EU countries can be divided into three categories, each with different exceptions. Figure 2.4 indicates the category to which each country belongs.

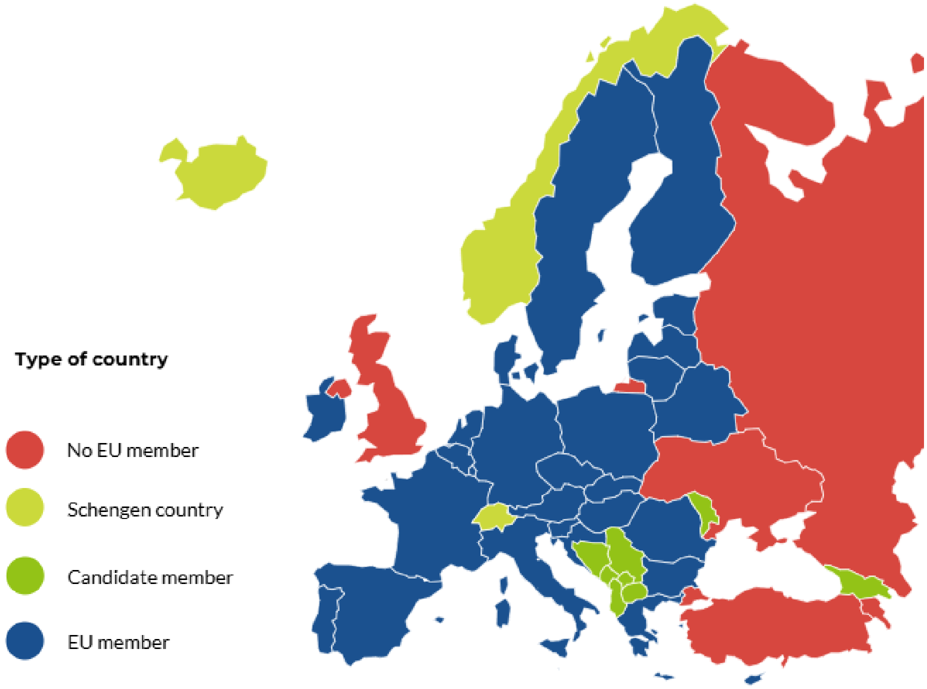



**Figure 2.4:** Members of the European Union and Non-EU members

The first category of special countries are the candidate members of the EU. These countries are working to gain access to the EU, but at this moment, they are not allowed due to procedures. These countries are most likely to join the ban on short-haul flights. If these countries join the EU, they are obliged to implement this law. Therefore, these countries are added to the list of those joining the ban.

The second group of countries are Schengen countries. These are countries that have joined the Schengen group and are in close contact with the EU members. However, further negotiations will need to be conducted with these countries regarding their participation. Generally, they are only affiliated with the free trade association, which does not obligate them to join the ban. However, since they already collaborate with the EU in many areas, it is unlikely they will oppose the ban. If it will lead to a reduction in CO2 emissions with no significant impacts on their hubs.

The last group are countries that won't join the ban on short-haul flight, because they aren't part of the EU. Additionally, these countries are not affiliated with the EU. The UK has recently left the EU and is therefore not obliged to comply with these laws. Ukraine has candidate member status, but due to the war with Russia, there is little chance of their actual EU membership. Alongside Ukraine, Turkey is also a candidate member of the EU. However, Turkey has never shown a serious commitment to meeting the conditions set by the EU for membership. Consequently, it is expected that they will not participate in the ban on short-haul flights.

These non-EU countries are expected to significantly impact the effectiveness of the ban, as they are not required to participate in the ban on short-haul flights. Consequently, routes to these airports remain viable, allowing short-haul flights to be operated between airports in non-EU countries and airports in EU countries. This is likely to undermine the impact of the ban on CO2 emissions.

### 2.3.2. Infrastructure of the High speed rail (HSR)

When passengers can no longer use an aircraft, there must be an alternative. A possible alternative is to encourage more train use, but what options are available, and what are there limitations?

In the world of rail, different types of trains operate on the tracks. For instance, local trains mainly facilitate regional transport. To travel between cities within countries, there are intercity trains that do not stop at every small station, unlike local trains. Finally, high-speed rail (HSR) also skips smaller cities and can travel at higher speeds between larger cities inland and across borders.
Research by Givoni & Banister (2006) indicated that high-speed rail (HSR) is a viable alternative to short-haul flights. Because the HSR can match the travel time of aircraft up to about 750 km (Adler et al. (2010)). Therefore, this study will primarily examine the role of HSR if a ban on short-haul flights is introduced. The only issue is that HSR cannot yet operate anywhere in Europe.

One of the reasons the HSR can't drive everywhere is that it needs to operate at higher speeds than normal trains. To accommodate this, special routes are required, allowing the HSR to reach speeds of up to 300 km/h. However, these routes are costly and have not yet been implemented throughout Europe. Consequently, the HSR sometimes has to traverse sections of track that cannot support its speed, leading to a lower average speed overall. Figure 2.5 shows a small indication of how the current network looks like.

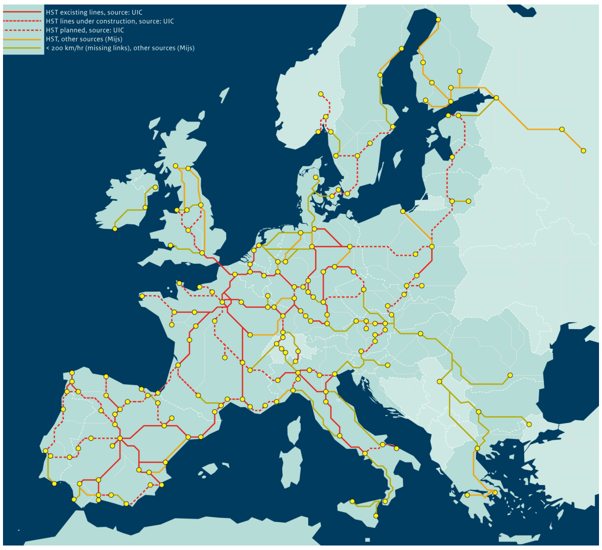



**Figure 2.5:** Current HSR network in Europe (Mijs (n.d.))

Figure 2.5 shows that only a small number of HSR lines have yet been built in Europe. Although there are many plans to improve this network, it is currently limited. If the ban is implemented now, it could create issues because the distance-based ban does not consider alternatives. This means banning all short-haul flights, could potentially reducing accessibility to certain European cities. With a time-based ban, this incomplete network will ensure that only a limited number of routes being affected, making the ban less effective.

### 2.3.3. Accessibility of the Air-Rail network

Givoni & Banister (2006) study argues that HSR could replace short-haul flights, but he emphasizes the need for collaboration with aviation. He suggests that, within the hub-and-spoke network, trains could substitute for short-haul flights. Considering the earlier example, what would this mean for passengers traveling between New York and Brussels? In this example, the route shown in Figure 2.6 is considered. A passenger wants to travel from New York to Brussels, with a transfer at Schiphol Airport. There are three options for this passenger if Air-Rail is also an available alternative.

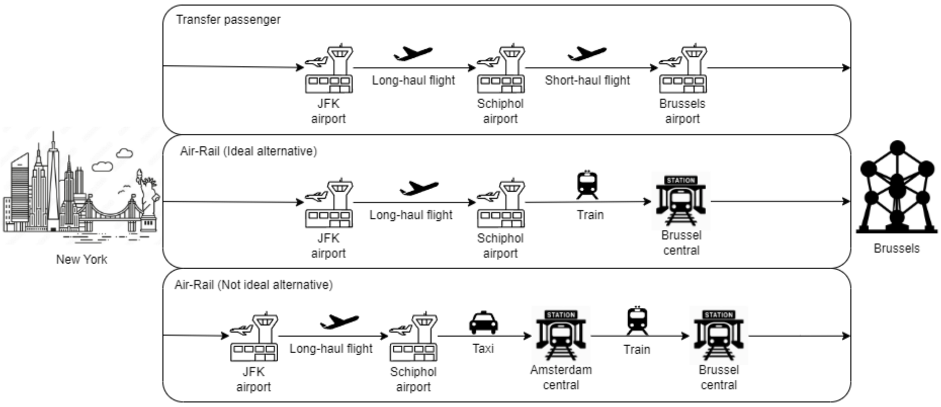



**Figure 2.6:** The difference between a passenger using Air-Rail network and a transfer passenger

For the Air-Rail network to be effective, having a station at the airport is ideal. This eliminates the need for passengers to travel to a nearby station, significantly reducing transfer time to the train. When there is no airport station, transferring becomes more difficult. As shown in Figure 2.6, in a sub-optimal scenario, passengers must first take a taxi to the city center before they can transfer towards the HSR, which is time-consuming and likely uncomfortable. Thus, this route can be considered not ideal.

For the High-Speed Rail (HSR) to serve passengers from the Hub-and-Spoke network, an airport station is likely necessary. Several airports in Europe already provide this option, but not all major hubs do. This gap could complicate the implementation of a ban on short-haul flights. To discourage continued flying, improving access to alternative transport methods is crucial. However, it remains uncertain whether passengers are willing to take a taxi to reach an HSR station. The impact of this on the ban's effectiveness has not been explored in current literature. But the study by Wang et al. (2020) stated that HSR stations at airports are essential for an effective Air-Rail network. Nonetheless, good accessibility to the HSR network at airports could be considered essential for a well-functioning Air-Rail network.

## 2.4. Expected effects of a ban on short-haul flights

The ban on short-haul flights will significantly impact the European transport market. The extent of this impact varies, but it will ultimately affect both operators and passengers. Several aspects and effects have already been discussed in this chapter. This section summarizes and assesses the found indicators to clarify which aspects this study will address.

### 2.4.1. Impact of the ban on route choices

Passengers will feel the greatest impact of the ban, but their choice behavior will also significantly affect the effectiveness of the ban. This behavior depends on the options available to passengers. Figure 2.2 illustrates an example of passengers wishing to travel from New York to Brussels. In this example, the ban is implemented to explore its implications for passengers' route choices. Figure 2.7 outlines how the ban influences the passengers route options.

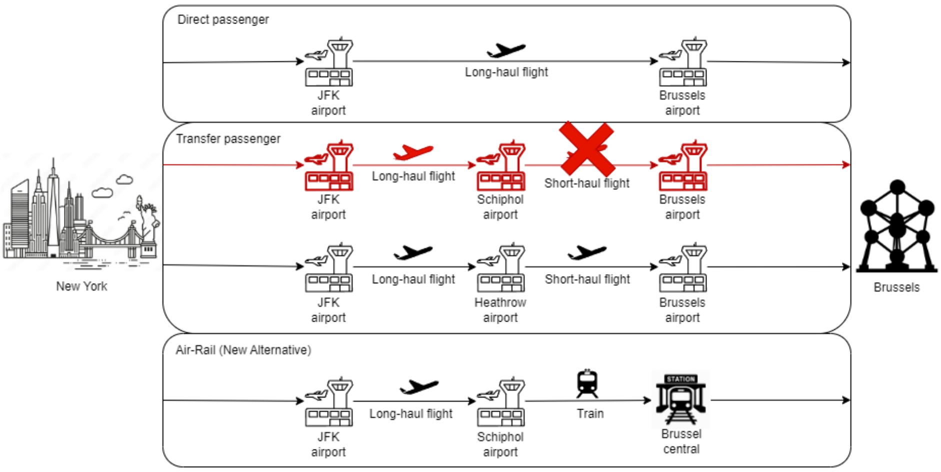



**Figure 2.7:** Route options for a passenger travelling between New York and Brussels when a ban on short-haul flights is in effect

Before the ban was introduced, the passenger's focus was mainly on the plane, as shown in Figure 2.2. Once the ban is in place, it will affect the available alternatives. Generally, the direct flight remains an option for the passenger, which should not hinder the ban's effectiveness. Since this direct flight does not involve a diversion and the passenger intends to make this trip, it is preferable to use a direct flight instead of multiple flights. After the ban is implemented, it is therefore desirable for passengers to choose direct options more often.

Figure 2.7 indicates that switching to a short-haul flight at Schiphol is no longer possible for passengers. This means that those who previously selected this option in Figure 2.2 must make a new choice. As mentioned earlier, opting for the direct flight is not a significant issue; it is still likely to lead to a reduction in CO2 emissions from aviation. The ban has also made a new alternative more appealing: the Air-Rail network, where passengers transfer to trains at Schiphol. This shift should result in fewer passengers using short-haul flights, contributing to a decrease in CO2 emissions from aviation. Additionally, this will help Schiphol maintain its hub function, providing economic benefits.

Despite the ban, the option of two flights remains available for passengers. As explained earlier, the policy does not need to be implemented in the UK. Consequently, passengers can fly to Heathrow in London and then continue to Brussels, which involves a short-haul flight. For the ban's effectiveness, this is undesirable, as CO2 emissions from the detour is very high. While the impact may be small in this example, but if London requires a longer detour than Schiphol to reach Brussels, it could become a significant issue. Assessing this impact is still challenging, as there is no literature addressing this effect.

In the example above, the passenger wanted to travel a route exceeding the ban's distance. However, some passengers may wish to journey a distance shorter than the ban. These passengers also significantly impact the ban's effectiveness and should be acknowledged. To illustrate their impact, Figure 2.8 depicts a scenario where a passenger wants to travel between Barcelona and Brussels, where a ban prevents direct flights between the two cities.

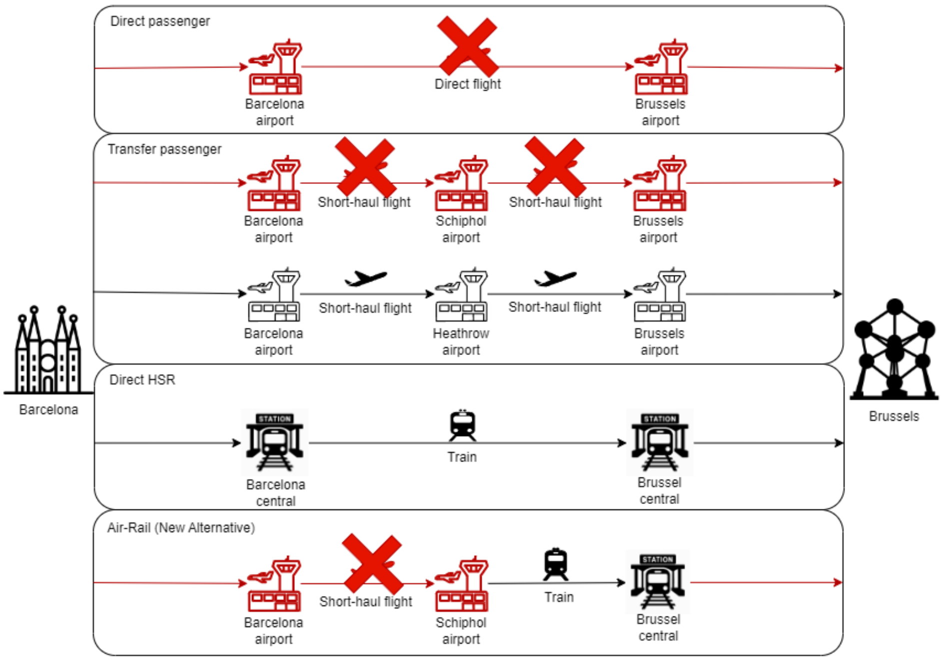



**Figure 2.8:** Route options for a passenger travelling between Barcelona and Brussels when a ban on short-haul flights is in effect

Figure 2.8 shows that the route options for this passenger have been reduced. The direct option and transfers are no longer available, and the Air-Rail network is also excluded. This leaves the passenger with only two options for travel between Barcelona and Brussels. The first option is to take a direct train connection between the two cities. This is a desirable choice for the effectiveness of the policy, as it ensures that the passenger no longer uses a plane and travels to their final destination by a cleaner mode of transport.

The second option is a transfer at Heathrow. This presents a major problem because this route involves two flights. As a result, if the passenger initially wanted to fly directly, they are now forced to reroute. This increases the journey's CO2 emissions, which is undesirable as it contributes to aviation pollution. The extent of this effect is difficult to predict and will depend on the speed of the two alternatives. If the train is faster than the two flights, only a small proportion of passengers may choose to fly this route. However, if it is quicker to fly via Heathrow, a larger group of passengers may opt for this option, leading to an increase in aviation CO2 emissions(Roman & Martin (2014)).

### 2.4.2. Impact of the ban on the hub-and-spoke network

For airlines operating more direct routes, the ban will likely have a greater impact than on others. This is because point-to-point airlines are less equipped to handle transfer passengers. Additionally, these operators often focus on shorter distances, which may be affected by the ban. This is likely to have a similar effect as seen in Finland (Baumeister & Leung (2020)), where most direct passengers shifted to using trains.

In Europe, most smaller airports serve airlines that use a point-to-point travel strategy. At these airports, transfers are rare, occurring mainly at hub airports. In Finland, researchers found that when short-haul flights are banned, people switch to other forms of transportation. This trend is likely among those using point-to-point airlines, as they may choose trains over planes. Therefore, while the focus on smaller airports is less important for this study, it's important to note that a ban will negatively affect their relevance in Europe.

For hub-and-spoke operators, the situation is likely to be different. When a passenger uses the hub-and-spoke network, this typically involves a journey longer than 1,500 km, meaning these passengers will not be equally affected by the ban. However, this changes when a passenger switches to a short-haul flight, in which case the ban does impact the passenger. As is shown in Figure 2.7. Here can be seen that the short-haul flight ban will influence passengers using the hub-and-spoke network.

Numerous hubs exist worldwide, with nearly every country having one. This provides passengers with various alternatives to bypass the ban. When a hub ceases to offer routes to a final destination, passengers are likely to select other routes through different hubs. Thus, it is crucial for the ban to be enforced in all countries in Europe. However, as explained in subsection 2.3.1, this is unlikely to occur. Consequently, hubs within EU member states may face unfair competition from those outside the EU. To strengthen EU hubs, promoting Air-Rail cooperation, as detailed in subsection 2.3.3, is beneficial. This will enable passengers to continue travelling through European hubs, helping to maintain the hub-and-spoke network within EU member states.

European hubs will be impacted by the ban on short-haul flights. The key question is whether this impact will be significant enough to cause several hubs to disappear. This relates to Givoni & Banister (2006) proposed alternative, which advocates for air-rail cooperation. However, current literature lacks information on whether the ban will encourage air-rail cooperation. Therefore, it remains uncertain if the hubs can continue to exist in EU member states when a ban on short-haul flights is implemented.

### 2.4.3. Impact of the ban on the rail sector

For rail operators, the impact of the ban is still difficult to assess. It is expected that the ban on short-haul flights will lead many passengers to choose high-speed rail (HSR), as those affected by the ban have limited alternatives. Consequently, these passengers are likely to opt for train travel, which could benefit train operators.

To provide a viable alternative to air travel, it is important that the infrastructure must be in place. Without it, passengers may resort to multiple flights to circumvent the ban. As shown in Figure 2.5, significant investment is still needed in Europe's infrastructure. Therefore, it remains uncertain whether HSR can serve as a suitable alternative.

If passengers wish to travel beyond the distance restricted by the ban, trains can accommodate them through effective cooperation with airlines. It is crucial that passengers can transfer to trains at airports; however, this is not currently possible at many major hubs in Europe, which may limit the utilization of the Air-Rail network. Furthermore, the network's usage is expected to decline due to the ban. Figure 2.8 illustrates this: if a passenger wants to travel between Barcelona and Brussels, they can currently still use the Air-Rail network. However, with the ban in place, the first flight they intended to take is no longer available, forcing them to seek other options. This results in lower frequency of use of the Air-Rail network than anticipated.

For train operators, the ban may lead to increased train usage. However, it could also result in reduced use of the Air-Rail network, ultimately decreasing the total number of passengers traveling by train.

## 2.5. Global overview of the impact of the short-haul flight ban

The aim of the ban on short-haul flights is to encourage the use of the HSR. Figure 2.7 and 2.8 indicate that passengers will still have the option to use HSR in both travel wishes shown in the figure. It is therefore expected that this study will demonstrate an increase in HSR usage following the introduction of the ban. For direct HSR connections, usage is likely to rise as the ban does not affect direct train journeys. This option is unlikely to lose passengers and may only see an increase. For the Air-Rail alternative, it remains to be seen whether the ban will lead to increased use of the Air-Rail network. Indeed, considering the route between New York and Brussels, the ban suggests that the Air-Rail network remains a viable option for passengers, potentially increasing the number of people travelling on it. However, when a passenger wishes to travel a distance shorter than the ban, the Air-Rail network option is no longer available. The question, therefore, is whether the use of the Air-Rail network will rise or fall.

There are also several expectations for aviation. For instance, the number of passengers wishing to take direct flights is likely to decrease. This is because the study primarily focuses on hub-and-spoke traffic, which is designed with few direct flights available, primarily towards the hubs. It is therefore expected that direct passenger numbers will decline, while transfer passenger numbers may increase. This is because the ban cannot eliminate all flights within Europe, leaving the option for passengers to fly around the ban. This could result in longer distances travelled by plane, leading to greater CO2 emissions. Several hubs within Europe will still be able to accommodate a large number of passengers as a result. However, hubs located outside EU countries are expected to experience growth, as they do not lose routes due to the ban, unlike those in EU countries.

Thus, it appears that the ban on short-haul flights could lead to a reduction in CO2 emissions, provided that the growth in HSR usage compensates for passengers flying around the ban. To assess the feasibility of this, this research will examine the choices passengers make while the ban on short-haul flights is in effect. This will involve assigning passengers to different routes and using the number of passengers on a route to calculate the average emissions from aviation sector when a ban is applied. This approach will also allow us to determine how many passengers choose to travel through specific hubs and which hubs will see an increase in passenger numbers due to the ban.

# 3 Methodology

The aim of this research is to calculate the indicators and their changes following the implementation of a ban on short-haul flights. This study will calculate different indicators based on the algorithm outlined in this chapter. The primary input data comes from Eurostat (2025), which provides information on the number of passengers flying between various airports worldwide in 2023.

The first step of this method is to calculate a base scenario in which no ban on short-haul flights exists. In this scenario, passengers are assigned to different desired destinations and locations they depart from. The routes taken to reach these destinations are then determined. Different ban scenarios are applied to this network to illustrate the effects on passenger choice behavior and other indicators.

This chapter begins by explaining the need for the base scenario and how it was created. After this introduction of the method, the different steps of the algorithm are discussed in detail. It then discusses the implementation of the ban within the algorithm.

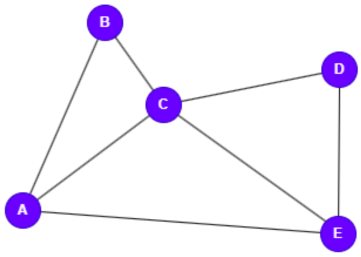
## 3.1. Base alternative

Models are generally never error-free. This is because they cannot fully capture the world's complexity. To correct the model's errors, existing data should be transformed into a scenario where the ban on short-haul flights has not yet been implemented. This allows for comparisons with the base scenario to assess the ban's impact on the previously mentioned indicators. Thus, this section first discusses the development of this base scenario.

### 3.1.1. Global overview of creating the base scenario

This research aims to assign passengers to their intended routes. Which means passengers are assigned to edges, where an edge is a route between two nodes. However, before going deeper into the methods, it is important to understand what constitutes a network and the terms associated with it.

To illustrate a network, an example has been created in Figure 3.1. It features five different nodes (A, B, C, D, E). Lines represent the connections between the nodes; these lines are called edges. The matrix adjacent to the network indicates which nodes are connected. In this matrix, 1 signifies that they are connected, while 0 indicates that they are not connected. The aim of the method is to eventually assign a quantity of passengers to each of the different edges, indicating their desire to travel over them.




| | A | B | C | D | E |
|---|---|---|---|---|---|
| A | 0 | 1 | 1 | 0 | 1 |
| B | 1 | 0 | 1 | 0 | 0 |
| C | 1 | 1 | 0 | 1 | 1 |
| D | 0 | 0 | 1 | 0 | 1 |
| E | 1 | 0 | 1 | 1 | 0 |

**Figure 3.1:** Example of a network, that exsists out of node and edges

Several steps are required to assign passengers to their new edges. To illustrate the necessary steps to make the algorithm, a brief overview of the various stages is presented in Figure 3.2. Each step in this figure comprises several additional steps, that will be explained later in this chapter. Keep in mind in this base scenario there isn't implemented a ban on short-haul flights.

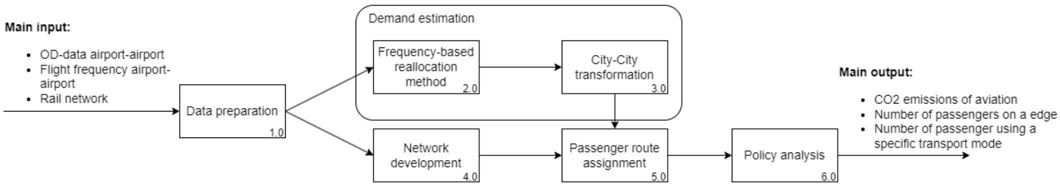



**Figure 3.2:** Main steps of the research

As illustrated in Figure 3.2, there are three different inputs necessary for the research. The first is Origin-Destination (OD) data between airports, this is the main input. Flight frequency is also necessary, and a rail network is necessary as a possible alternative input. The first step (block 1.0) aims to transform the data into a usable format. This is necessary because the data arrives in different formats. It is also important to estimate some of the data. Based on this, the network will be built. The choices made in this step are therefore relevant to consider.

The model's outcomes will be generated through a series of steps divided into two distinct routes. The route through blocks 2.0 and 3.0 calculates demand between various cities, while block 4.0 focuses on network development. Both routes converge in block 5.0, where the results are combined to assign passengers to different edges. This result can then be analyzed in block 6.0.

At the beginning of this chapter, it was indicated that the data used for this model is from Eurostat (2025) and consists solely of passengers traveling between two different airports. To adjust this data to a format suitable for passengers wishing to travel between two different cities, two steps are necessary. The first step, indicated in block 2.0, is required because the original data does not account for transfer passengers. As a result, passengers taking multiple flights are counted twice. To ensure that each passenger is counted only once in the model, the Frequency-based reallocation method was used. This newly developed method is specifically designed for this study because no existing method was found in the literature that could straightforwardly reallocate transfer passengers to their original origin and destination in an OD matrix.

When the data is adjusted for transfer passengers, it still doesn't indicate the origin or destination of a passenger. In block 3.0, an attempt will be made to assign different passengers to two cities between which they wish to travel. The city-to-city method is based on previous research by Grolle (2020). The result of this step is an OD matrix in which passengers are assigned to their desired travel cities.

The initial step in developing the infrastructure begins with establishing the network (block 4.0). In this block, the rail and air networks will merge into a single connected system. This network will consist of various nodes and edges. The nodes represent airports and cities, while the edges represent possible rail or air routes.The value of these edges represents the travel time that is needed to complete a specific edge. Not all nodes are interconnected; therefore, a car network is included to represent, in some cases, the final leg of travel between a city and an airport. The study focuses on trains and planes, which is why cars are only used to connect cities and airports. While passengers can travel between two cities in Europe by car, it is unlikely they would fly from New York to Schiphol and then drive to Barcelona. For this reason and to simplify the model, car travel is not included on a large scale but is considered only as a means of reaching the airport.

With these networks established, it is time to calculate the likelihood that passengers will choose specific routes. This calculation is conducted in the block entitled Passenger route assignment (5.0).
The first step in block 5.0, is to determine the different routes passengers can take. The routes are based on travel time, as airfare costs are difficult to estimate. A shortest path algorithm identifies the fastest route between different cities. From these routes, a top 5 will be created, which will then be compared with one another. In this comparison, a probability is assigned to each route, the probability will be calculated using the Random Regret method (RRm). This probability will then be multiplied by the number of passengers wishing to travel between the cities, allowing us to add the passengers to the different edges they travel.

Once passengers are assigned to their edges, the network can be analyzed (block 6.0). The purpose of this analysis is to determine the values of various indicators. This will involve calculating CO2 emissions and examining the number of passengers travelling through each hub to ultimately provide advice to airports. Additionally, it will assess the difference in emissions generated per ban.

## 3.2. The preparation of the data needed for the algorithm

This study requires various data to calculate different aspects. The data fed into the model must first be prepared to ensure it is in the correct format for the algorithm's calculations. Additional information must also be extracted from the data, which is necessary for the algorithm's use. Figure 3.3 illustrates the steps to prepare the data. The upper flow represents the collection of aeronautical information, while the lower flow pertains to railway data.

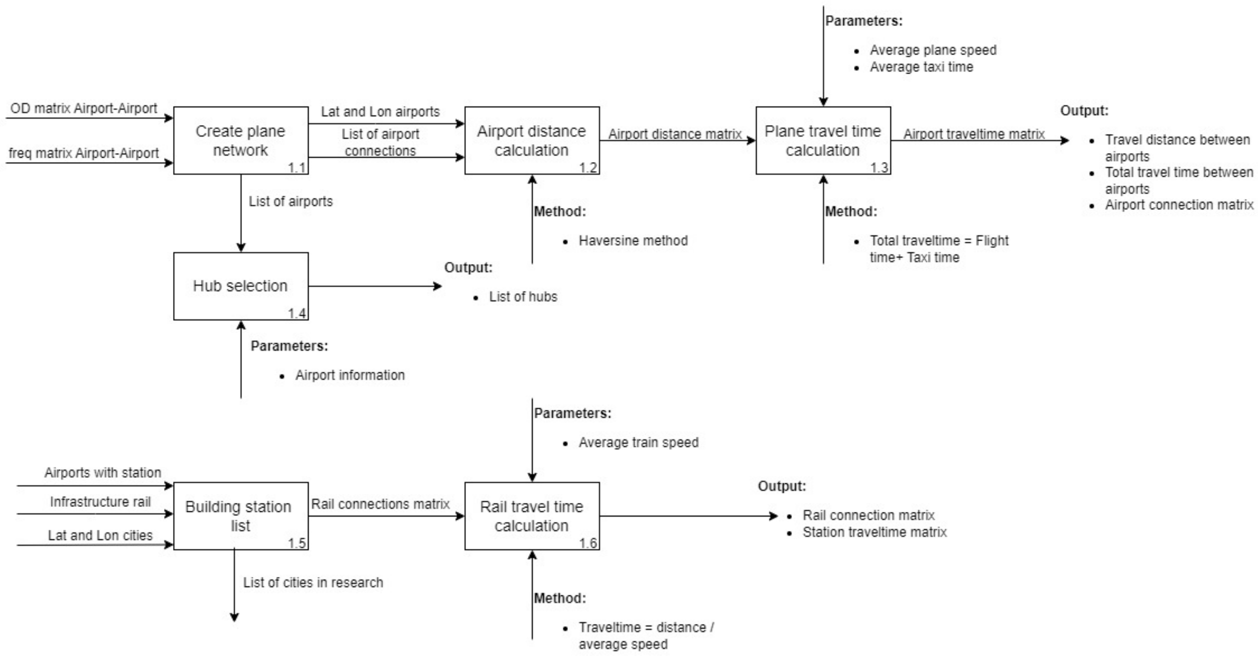



**Figure 3.3:** Block diagram (1.0): Data collection

The primary data for this study is the OD airport data, from included hubs in this study. The data consists of the number of passengers transported from the hub to another airport. Several adjustments were made to simplify the dataset. First, the data is from the year 2023, obtained from Eurostat (2025). A key adjustment is the removal of smaller airports that are not relevant to this study. Deletions may occur for various reasons; for example, an airport may only offer routes to less significant airports. Chapter 4 will explain these reasons in more detail. This chapter will also explain which hubs are selected for this study.

Because the data was only obtained from the hubs, several assumptions were made. One assumption is that the same number of passengers depart from the hub as arrive. This means that if the data indicates that hub A receives 100 passengers from airport B, then 100 passengers also travel from hub A to airport B.

The frequency of flights was obtained from Eurostat (2025) and approached in the same manner as the passenger OD matrix. The data consists of actual flights operated in 2023, except for the data from the Uk this is from 2019. The reason for this difference will be explained in chapter 4

| **What** | Taxi Time | Stop Time Train | Average speed plane | Average speed train | Tolerance level | Tolerance level non-EU |
|---|---|---|---|---|---|---|
| **Value** | 15 min | 15 min | 700 km/h | 220 km/h | 50 km | 100 km |

**Table 3.1:** Parameters

In the OD data, several trips between different airports were indicated. To know how long a journey takes between two airports, an average speed was used. To use this speed, the distance between two flights was first calculated. These calculations were done using the haversine method. This distance was then divided by the average speed. To finally get a total time, the average taxi time was added to this. In the end, two different matrices emerge from this. The first is a matrix with distances between different airports. The second is a matrix with travel times between different airports.

For the train, the input data consists of several aspects. The primary component is the HSR network, which includes connections between different cities. The train connections are based on data from Grolle (2020) and from Interrail-Eurail (2024). Along with the locations of the stations, the distances and travel times between them can be determined. This is derived in the same manner as flights, except that instead of taxi time, a stop time has been included. This stop time accounts for the need to change trains and for trains stopping at different stations. The stop time train value can be found in Table 3.1

Several methods were used to estimate the parameters in Table 3.1. For the average speeds, previous reports by Donners (2016) were considered. To arrive at the average taxi time, the average taxi times for Schiphol Airport, Munich Airport, Madrid/Barajas Airport, and Heathrow were taken into account. These average taxi times were obtained from Eurocontrol (2022).

The tolerance area indicates that airports situated within the city centre's radius belong to that specific city. The outer tolerance was selected to ensure all airports are linked to major cities, within the same country. This decision was made by analysing the map and adjusting the value until it provided a realistic representation. In Europe, the tolerance is smaller due to the proximity of cities. This value is derived from desk research (Google (2025)).

The stopping time of the train is determined by two components. The first is that the train must stop for a time at each station to allow passengers to board and alight. This stop takes about 5 minutes, which includes opening and closing the doors. In this study, specific lines will not be considered, as it is common for passengers to change trains. Therefore, an additional 10 minutes has been added per station to account for possible transfers. Combining these factors, a total of 15 minutes is added for each segment of the HSR.

## 3.3. The methods for the demand estimation

The demand is estimated in two different steps, these two steps are discussed below. The first step explains the development of the frequency-based reallocation method. The allocation of airport data to various cities is then addressed.

### 3.3.1. Frequency-based reallocation method

The data obtained for this study doesn't account for transfer passengers. To rectify this data, the Frequency-based reallocation method was developed to transform the data. This subsection will describe the Frequency-based reallocation method. This will be achieved by first outlining the method and then illustrating it with a small example.

The issue addressed by this method is that passengers with transfers are double counted in the current data. If this is not corrected, it will result in an overestimation later in the study. The aim of this method is to assign passengers in the OD matrix to their airport of departure and likely their actual final destination. The rescheduling is based on the likelihood that a passenger has a subsequent destination. This likelihood is determined by the airport outflow. For example, if 70 people fly from airport A to airport B and 30 people fly from airport A to airport C, the probability of a passenger flying to airport B from airport A would be 70%. The formulas of this method can be found in Equation 3.1, 3.2 and 3.3.

**Frequency-based demand correction method**

$$N_{ij} + T_{ij} = D_{ij} \qquad \forall i,j \in N \qquad (3.1)$$

$$X_{ij} * (1 - (trans_j * Hub_j)) = N_{ij} \qquad \forall i,j \in N \qquad (3.2)$$

$$\sum_{n \in N} X_{in} * trans_n * Hub_n * \left(\frac{X_{n,j}}{(\sum_{m \in N} X_{nm} * Fly_{i,n,j}) - X_{in}}\right) * Fly_{i,n,j} = T_{ij} \qquad \forall i,j \in N \qquad (3.3)$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $N$ | Sets of airports where: $n, j, i \in N$ |
| $D_{ij}$ | Demand between city i and j |
| $T_{ij}$ | Passeners with a transfer traveling between city i and j |
| $N_{ij}$ | passengers traveling without a transfer between city i and j |
| $trans_i$ | Transfer rate at airport i |
| $Hub_i$ | 1 if airport i is a hub zero otherwise |
| $Fly_{i,j,n}$ | 1 if a passenger can transfer towards route n to j, after traveling on route i,n. Zero otherwise |

The basic formula of this method is Equation 3.1. It states that each box in the OD matrix consists of a group of passengers who have flown directly to the destination ($N_{ij}$) and a group of passengers who have travelled via transfer between cities ($T_{ij}$). $N_{ij}$ is calculated by subtracting the number of transferring passengers from the total already assigned to this spot in the OD matrix (Equation 3.2). The number of transferring passengers is calculated by multiplying the hub's transfer rate by whether location j is a hub. This value is then subtracted by 1 and multiplied by the total number of passengers already assigned to a specific spot in the old OD matrix.

The proportion of passengers making a transfer will be reallocated to a new position in the OD matrix. Equation 3.3 illustrates how this reallocation occurs. This calculation consists of two parts. The first part determines the number of passengers wishing to transfer, while the second part assesses the probability of the potential final destination.

The probability is calculated by dividing the number of passengers on each route by the total number of passengers leaving the airport. Before the probability can be calculated, the total must first be checked for two aspects. First, it will be verified whether the transfer is a logical one. For example, if someone flies to Schiphol from Africa, it should not be assigned to a flight back to Africa. To prevent this, areas are marked as prohibited, which vary depending on the departure point of the first flight and are defined as corner-based. If a passenger can transfer to a specific airport is calculated by using the Dynamic Restricted Area method. Appendix C provides a detailed explanation of how this Dynamic Restricted Area method works. The second aspect to consider is that the outbound flight is not included in the total, as this flight does not affect the choice of transfer. In summary, the total number of passengers leaving the airport is adjusted for unrealistic flights and the first flight.

After calculating $T_{ij}$ and $N_{ij}$, these values can be summed for all airport combinations, yielding the number of passengers traveling between the two airports. To ensure that $D_{ij}$ and $D_{ji}$ are equal, the average of these two values is included in the OD matrix. This results in an OD matrix of the airport data that accounts for transfer passengers.

#### Example Frequency-based reallocation method

Figure 3.4 presents a small example that illustrates how the data is adjusted for transfer passengers. In this example, node C is a hub with a transfer rate of 0.4. The example aims to calculate how many passengers travel between airports A and E.

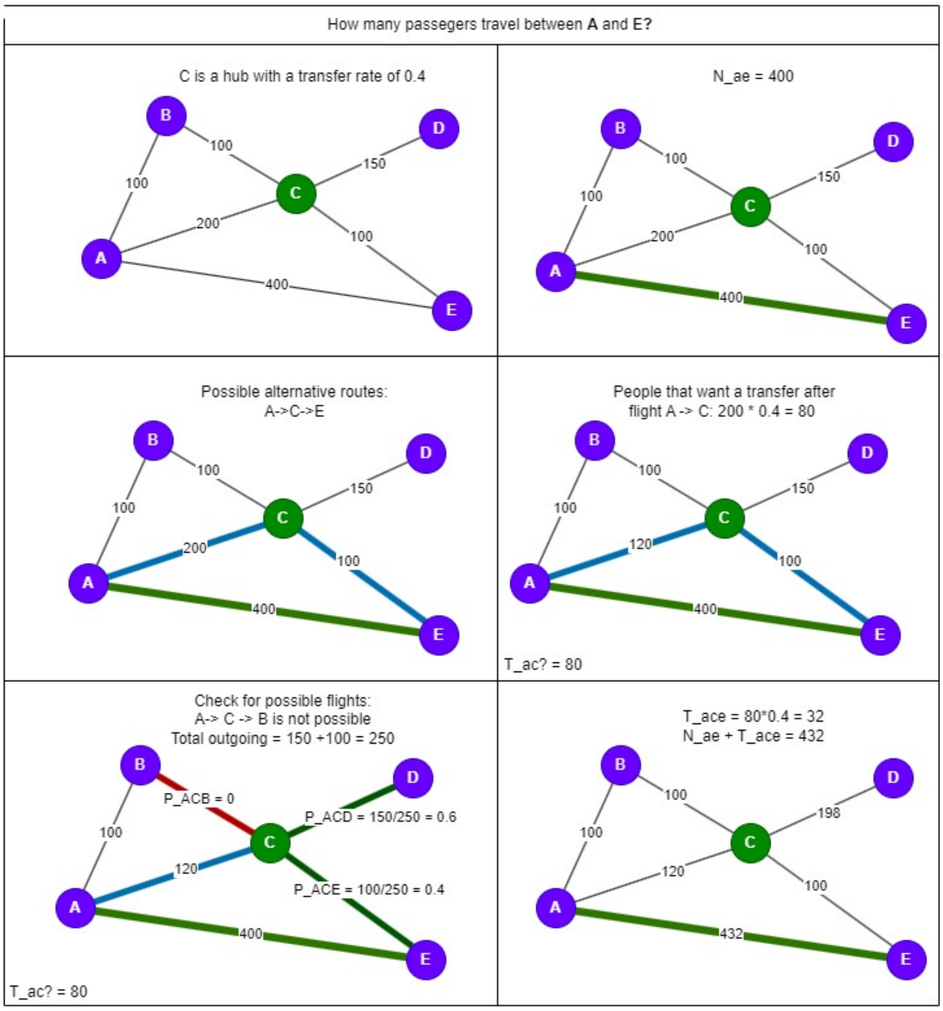



**Figure 3.4:** Example: Frequency-based reallocation method

### 3.3.2. City to City assignment

After correcting the airport data, it is still important to link airports to cities. This correction ensures that passengers ultimately have a final destination. The idea behind this transformation is that each airport has its own service area, meaning that an airport can serve several cities, or a city can be served by several airports. The methodology used is based on the study Grolle (2020), with a few minor modifications. This section will briefly discuss the design of the method and the choices made. The formulas of the different steps can be found in Appendix B. The steps to transform the data into city to city data are shown in Figure 3.5.

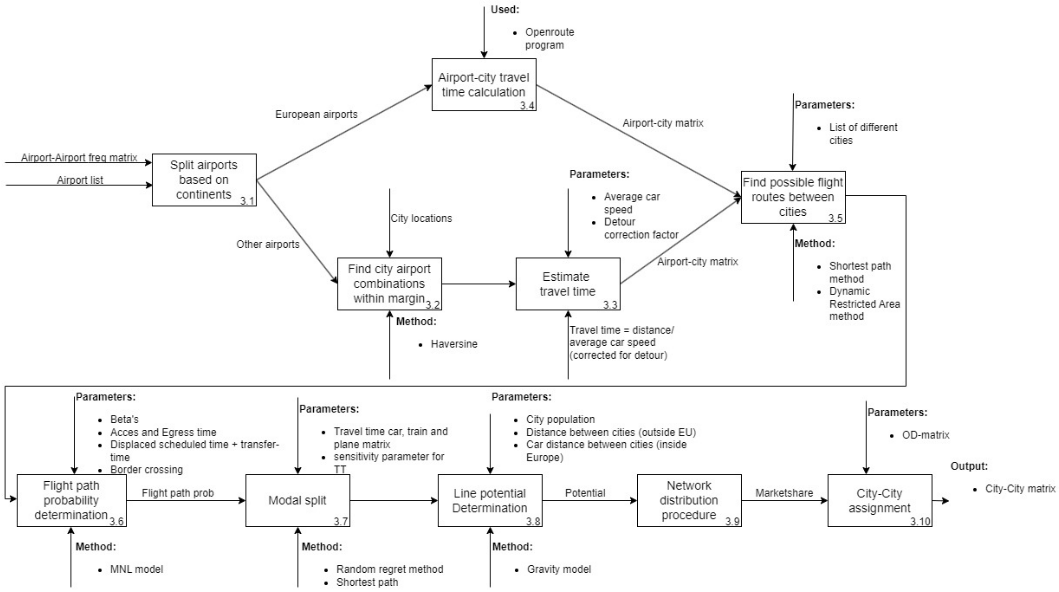



**Figure 3.5:** Steps of the City to City transformation method

The initial steps were organised to collect the final data. Block 3.1, for instance, examined the locations of the airports and the continents on which they are located. This data is important for estimating car routes and for designing the ban.

The determination of car routes is based on the continent where the airport is located. Specifically, airports in Europe are assessed using the information form HeiGIT (2024) (block 3.4), which algorithm calculates travel time between two points, similar to a navigation system. When an airport can be reached within 2.5 hours from the city centre, the two are linked, indicating that the city can be served by passengers from the connected airport.

For airports outside Europe, this connection is established by drawing a 100 km radius around the city centre (blocks 3.2 and 3.3). When an airport falls within this radius, the travel time between the city and the airport is estimated by dividing the distance by an average car speed, adjusted for detours. Within Europe, open borders facilitate easier access for passengers to board flights in other countries. Outside Europe, this is often not the case, making it unlikely for people to travel to other countries to catch a flight. Therefore, it was decided to link airports outside Europe only to cities located within the same country.

The final step in collecting the data is finding all the routes a passenger can take between two cities by plane. This was accomplished using a Depth-First Search (DFS) function to determine all possible flight routes. However, to narrow down the results, two criteria were added to the algorithm. The first is a maximum number of transfers, and the second is that the transfers must be logical. The maximum number of transfers was set on a maximum of two transfers on one route. The logic of the transfers was determined using the Dynamic Restricted Area method, as explained in Appendix C. The outcome of this method is a list of possible flight routes between two cities. To prevent infinite searches for possible routes, a maximum of 10,000 iterations was selected.

The first step of the city-city transformation method is to calculate the probability of a passenger taking a specific air route (block 3.6), between different cities. The probability is calculated using an MNL model. Where several indicators are used, to calculate the probability of a passenger taking a particular route.

The utility is based on three different aspects, the access and egress time, the Displace Schedule Time with transfers and whether they have to cross the border. After calculating the Utility, this can be converted to a probability of taking a specific route. The formulas for this step are Equation 3.4 and 3.5

**Utility function**

$$U^{fp}_{i,x,y,j} = \alpha_1 \cdot \left(t^{acs}_{i,x} + t^{acs}_{i,x} \cdot BB_{i,x}\right) + \alpha_2 \cdot \left(t^{egr}_{y,j} + t^{egr}_{y,j} \cdot BB_{y,j}\right) + \alpha_3 \cdot t^{DST}_{x,y}, \quad \forall\, r \in R \tag{3.4}$$

$$p(m) = \frac{e^{-U^{fp}_{i,x,y,j}}}{\sum_{l \in R} e^{-U^{fp}_{i,x,y,j}}}, \quad \forall\, r \in R \tag{3.5}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $t^{acs}_{i,x}$ | Access time between $v_i$ and $ap_x$, |
| $t^{egr}_{y,j}$ | Egress time between $ap_y$ and $v_j$, |
| $BB_{i,x}$ | Border barrier between $v_i$ and $ap_x$; (0 if same country, else 1), |
| $BB_{y,j}$ | Border barrier between $ap_y$ and $v_j$; (0 if same country, else 1), |
| $t^{DST}_{x,y}$ | Displaced schedule time for route between $ap_x$ and $ap_y$; $\left(\frac{1}{4}\right.$ of headway $\left.h_{x,y}\right)$ . |
| $p(m)$ | Change that route m is chosen |

Travelling between two cities can be accomplished by various transport modes. For this study, three transport types were selected for passenger travel: car, train, or plane. In the block modal split (block 3.7), the probability of a passenger using a specific transport type will be calculated. This calculation has been performed using a Random Regret method, as it considers the alternatives that the passenger did not choose. The calculations are based on one attribute: travel time. Within this study, a constraint has been added to the modal split, as people are unlikely to travel between different continents by car or train. It was decided to allow train and car travel only if the trip is between two cities within Europe; in all other cases, the entire transport choice is allocated to air travel. The travel time for rail, is found by using a Dijkstra shortest path method. The travel time by car is determined using data from Grolle (2020). The formulas used for this step are Equation 3.6 and 3.7

**Random regret equations**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln\left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall\, r \in R_{eu} \tag{3.6}$$

$$P(m) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R \tag{3.7}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R_{eu}$ | Set of all available route options that start and end in Europe |
| $P(m)$ | Change that route $m$ is chosen |

With the probability of a specific route and the likelihood of someone choosing to fly, there can be started to assess the potential for travel between two different cities using a specific route. To calculate this potential, the gravity model formulated by Donners (2016) will be employed. The potency represents the relative share of passengers wishing to travel between cities X and Y on a specific flight route. The formulas used for this step are Equation 3.8 and 3.9

**Line Potential Determination**

$$MS_{i,j}^{\text{air, est}} = P(m) \tag{3.8}$$

$$\text{Potential}_{i,x,y,j} = MS_{i,j}^{\text{air, est}} \cdot \left( \frac{v_i^{\text{pop}} \cdot v_j^{\text{pop}}}{DS_{i,j}^{\text{road}} \, / \, f_{\text{car}}^{\text{detour}}} \right) \cdot p(m) \tag{3.9}$$

Where:

| Variable | Meaning |
|---|---|
| $Potential_{i,x,y,j}$ | Represents a relative number of passengers that would like to take the flight from $ap_x$ to $ap_y$ When travelling between cities $v_i$ and $v_j$ |
| $MS_{i,j}^{air,est}$ | Indicates the change of passengers that would opt for a flying option |
| $v_i^{pop}$ | Population of city $i$ |
| $DS_{i,j}^{road}$ | Distance between city i and city j |
| $f_{car}^{detour}$ | Detour factor car |

Now that the proportion of passengers wishing to travel between two cities is known, it is important to translate this to the specific routes. This allows for the calculation of market share on each flight route between the two cities. The calculation is done by summing the potentials of the different routes on a specific leg. The potential of each route is then divided by the total potential, resulting in a market share for that specific route. Thus, the market share of passengers on a leg, wishing to travel between the two specific cities is known. The formula for this step is Equation 3.10.

**Marketshare calculation**

$$\text{Marketshare}_{i,x,y,j} = \frac{\text{Potential}_{i,x,y,j}}{\sum_{i \in V^{2.5}} \sum_{j \in V^{2.5}} (\text{Potential}_{i,x,y,j})} \tag{3.10}$$

**City city demand calculation**

$$DM_{i,j}^{\text{air}} = \sum_x \sum_y \left( \text{Marketshare}_{i,x,y,j} \times N_{x,y}^{\text{pax}} \right) \quad \forall \quad x, y \in AP \tag{3.11}$$

Where:

| | |
|---|---|
| $DM_{i,j}^{air}$ | The amount of passengers traveling between city i and j |
| $Marketshare_{i,x,y,j}$ | The market share on route i,x,y,h |
| $N_{x,y}^{pax}$ | The amount of passengers travelling on edge x and y |
| $AP$ | Set of flight paths |

Ultimately, the market share for each leg will be multiplied by the number of passengers travelling on that leg, as shown in Equation 3.11. For each combination of cities, these routes will be summed to determine the number of passengers flying between different cities. This gives a OD-matrix, that represents the demand between different cities.

The algorithm developed by Grolle (2020) accounts for other possible modes of transport; however, this study chose not to do so, as it focuses on transfer passengers in the air market. Consequently, passengers using other forms of transport are not relevant for this study.

## 3.4. Network development

Determining which routes passengers choose requires a network. This section briefly explains how to build this network, aiming to develop a closed system. It will first describe the different nodes, followed by an explanation of how to construct the edges.

The network will consist of three different types of transport modes, which can travel through two types of locations. These locations, as explained earlier, are represented by nodes. The nodes in the system can represent two things. The first is a city centre, which can be seen later in the model as a passenger's starting or ending point. This node also represents an HSR station in the middle of the centre. The second type of node is an airport; the airport cannot be characterised as a starting or ending point, meaning that it functions solely as a transit node.

The edges represent the possible routes between different nodes. These edges can indicate an air route or a train route. In some cases, they may represent a car route if a train option is not available for a journey to the city center.

Each edge is assigned a unique value. To select a route, a passenger aims to navigate the system while keeping this value as low as possible. Determining what this value should represent is complex. Flodén et al. (2017) found through a literature review that travel cost is the most significant factor influencing people's mobility. However, calculating travel costs for flights is challenging due to the numerous providers and different sellers of the same tickets, making price prediction difficult. Other factors suggested by Flodén et al. (2017) include travel time and comfort. A study by Roman & Martin (2014) found that travel time is the most important factor for passengers regarding Air-Rail integration. Therefore, travel time has been chosen as the main variable. This means the value of edges represents the travel time between nodes, considering the specific transport mode used. Comfort is also factored into travel time, but this will be discussed later.

The network comprises an air network and a rail network. Since not all airports are connected by trains, in some cases, cars are also included to connect all nodes in the network. The travel time by car is calculated in the same way as in the city-to-city transformation method.

The result of this network development. Is that there are now different nodes between them edges with travel times. In the next step will this travel time be used to find the fastest routes between two cities.

## 3.5. Route assignment

With the networks created, it is possible to assign passengers to the various edges. This means that each edge is allocated a quantity of passengers to travel over it. This allocation will be carried out in several steps, as illustrated in Figure 3.6. This section will explain what occurs at each step and the decisions made during them. The passenger route allocation process is divided into three steps.

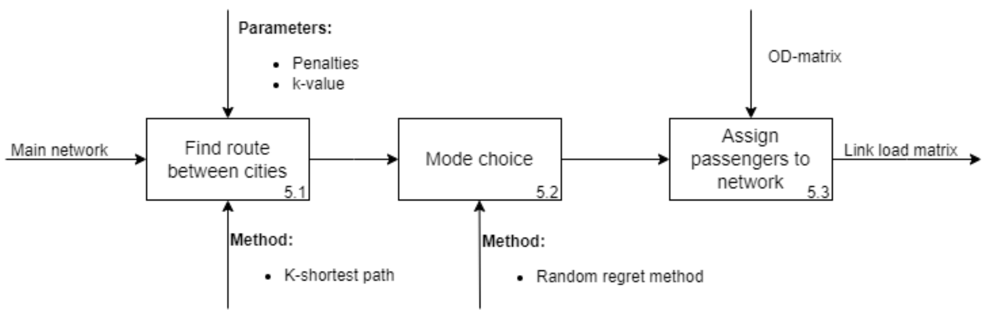



**Figure 3.6:** Block diagram: Passenger route assignment

The first step involves the system searching for different routes. This search will be conducted for all possible city combinations. The method employed is based on Dijkstra's shortest path algorithm, specifically the k-shortest paths method. The idea is that when the fastest route is identified, it is stored and cannot be traversed again. After saving the shortest path, a new shortest path is sought. This process is repeated until k amount of routes are found. For this study, the researcher chose a k value of five. This means that five routes are searched for each combination of cities.

To prevent the algorithm from getting stuck, a maximum number of iterations has been set at 1500 iterations. Once this maximum is reached, the algorithm will proceed to the next combination of cities. This also ensures that not all city combinations will have exactly five routes, as this can vary due to the maximum number of iterations.

The network only uses travel times between cities. The issue with relying solely on these times is that a passenger also experiences other forms of travel time. Consequently, several penalties have been incorporated into the k-shortest path algorithm. These penalties ensure that when a route passes through specific combinations of nodes, extra time is added to the total travel time. Table 3.2 summarises the different penalties that are applied.

| No. | Reason for the penalty | Between | Penalty Time |
|---|---|---|---|
| 1 | If an airport isn't a hub | Airport-Airport | +2 hours |
| 2 | If a taxi ride is taken to a city that isn't the city of the airport, and isn't the final destination | Airport-City-City (where the airport is) | +10 hours |
| 3 | Access time airport with train | City-Airport (with HSR station) | +2 hours |
| 4 | Access time airport with car | City-Airport (without HSR station) | +3 hours |
| 5 | Egress time airport with train | Airport (with HSR station)-City | +1.25 hours |
| 6 | Egress time airport with car | Airport (without HSR station)-City | +0.75 hours |
| 7 | Air-Rail transfer on an airport without HSR station | Plane-Taxi-HSR | +1.5 hours |
| 8 | Air-Air transfer | Airport-Airport-Airport | +1 hour |

**Table 3.2:** Different penalties in the model

Penalty 1 is based on the fact that at smaller airports, it is more complicated for passengers to transfer. This requires a passenger to leave the airside first and then check in again. Therefore, it was decided to grant all airports that do not have a hub function an extra 2 hours of transfer time.

Penalty 2 has been introduced to prevent the creation of unrealistic routes. This correction means that if someone lands at an airport connected to a city, such as Amsterdam, then travels by taxi to another city, such as Utrecht, and subsequently takes the HSR back to Amsterdam. What a odd transfer choice is, but what is possible due to the algorithm's structure. To prevent this from happening, a 10-hour penalty has been applied if this scenario occurs. This adjustment is necessary because such a switch is illogical and can make the results not realistic.

Penalties 3, 4, 5, 6, 7, and 8 are based on the times that are needed to switch between different transport modes in a node. The reason these values are chosen are discussed in Appendix F.

With the routes determined and penalties added, there are ultimately five fastest routes for passengers, to travel between two specific cities. Now that the possible options are known, it's time to calculate the mode choice using the Random Regret method (RRm). This method is not widely used in similar research, though it is sometimes employed by consultants. Its advantage lies in accounting for the regret passengers feel about unchosen options, unlike the MNL model, which evaluates each route independently without considering other choices. Additionally, the MNL model is challenging to apply when different route options are similar, making the RRm model more effective. Another benefit of this method is that it bases regret solely on the travel time required to complete the route, simplifying its application while accurately estimating the probability of someone choosing a specific route. The used formulas to calculate the RRm are shown in Equation 3.12 and 3.13. The only attribute included is the travel time, which is assigned a beta of 0.01. This beta is taken from the study of Grolle (2020), which used this beta for his City-to-City demand estimation.

**Random Regret formulas**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln\left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall\, r \in R \tag{3.12}$$

$$P(r) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R \tag{3.13}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R$ | Set of all available route options |
| $P(r)$ | Change that route $r$ is chosen |

With the probabilities for the different routes calculated, the final step of the mode choice is to assign passengers to the appropriate edge using Equation 3.14. At this stage, the probability of a passenger taking the route is multiplied by the number of passengers travelling between the two cities. The number of passengers for each route will then be allocated to the various edges it takes, and this will be done for all the routes. In the end, the number of people travelling over each specific edge will be known. The formula for this step is shown in Equation 3.14

**Allocation of passengers to different edges formula**

$$f(e) = \sum_{R \in \mathcal{R}_e} P_r \cdot \text{OD}_{i,j}, \quad \forall\, i, j \in I, \tag{3.14}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $R$ | A specific route |
| $\mathcal{R}_e$ | Set of routes that pass through edge $e$ |
| $P_r$ | Probability of selecting route $R$ |
| $\text{OD}_{i,j}$ | Number of passengers wanting to travel between city i and j |
| $e$ | An edge in the network |
| $f(e)$ | Total passenger flow assigned to edge $e$ |
| $I$ | Set of cities |

Once all passengers are assigned to different edges, this part of the algorithm is complete. From these calculations, a Link Load Matrix is generated, which can then be used to calculate the various indicators, in the policy analysis. This Link Load matrix consists of the amount passengers travelling on edges between different nodes within the network.

## 3.6. Policy analysis

The final step in creating the base scenario is the policy analysis. In this phase, the various indicators identified in chapter 2 are calculated using the Link Load Matrix. The three indicators are calculated differently, and each is discussed below.

The first indicator calculated by this algorithm is CO2 emissions from aviation in Europe. Equation B.25 was used to compute these emissions. This formula checks for passengers on each air route. If there are passengers, their number is multiplied by the distance of the route, and this result is then multiplied by an environmental constant representing the average emissions per passenger per kilometre. The CO2 emissions from all flight routes are summed to produce a total.

**Formula to calculate the CO2 emission of the aviation market**

$$TE = \sum_{e \in \mathcal{E}_{\text{air}}} f(e) * AE_{air} \tag{3.15}$$

Where:

| Variable | Meaning |
|---|---|
| $TE$ | Total emissions of airplanes in Europe |
| $AE_{air}$ | Average emissions per passenger per flight km |
| $\mathcal{E}_{\text{air}}$ | Set of edges that represent flight routes |

To calculate the number of passengers using a hub, the total number of passengers departing from it is counted. This total reflects the frequency with which passengers travel through the hub. To assess the choice of transport mode, each route was examined individually. Once a passenger was assigned to a specific route, the number of passengers using that transport mode was also recorded. The used formulas for these steps are Equation 3.16 and 3.17

**Formula to calculate departing passengers**

$$N_i^{\text{out}} = \sum_{j \in J} D_{i,j}^P, \quad \forall\, i \in H \tag{3.16}$$

| Variable | Meaning |
|---|---|
| $N_i^{\text{out}}$ | Total number of passengers departing via hub $i$ |
| $D_{i,j}^P$ | $Passengers travelling between airport i and j$ |
| $H$ | Set of all hubs |
| $J$ | Set of all possible airports |

**Formula to calculate number of passengers using a specific transport mode**

$$M^T = \sum_{r \in \mathcal{R}} P_r \cdot \text{OD}_{i,j}, \quad \forall\, t \in T \tag{3.17}$$

| Variable | Meaning |
|---|---|
| $M^T$ | Total number of passengers using transport mode $T$ |
| $P_r$ | Probability of selecting route r |
| $OD_{i,j}$ | Number of passengers wanting to travel between city i and j |
| $I$ | Set of cities |
| $R$ | Set of routes |
| $T$ | Set of all transport modes: {Train, Plane, Plane+Transfer, Air-Rail} |

The results of these calculations are different values of the indicators that can be used for comparison with other scenarios. The latter calculations established the base scenario. Calculating the prohibition scenarios requires adjustments to the network design, which will be addressed in the next section.

## 3.7. Ban on short-haul flights

With the base scenario in mind, work can begin on designing the scenario's for the ban on short-haul flights. As mentioned earlier, this study will examine two approaches to banning short-haul flights. Both versions require different calculations to determine the banned routes. This section will discuss how the ban is implemented in the model. Figure 3.7 provides an overview of the changes made to the algorithm to calculate a scenario in which a ban on short-haul flights is implemented.

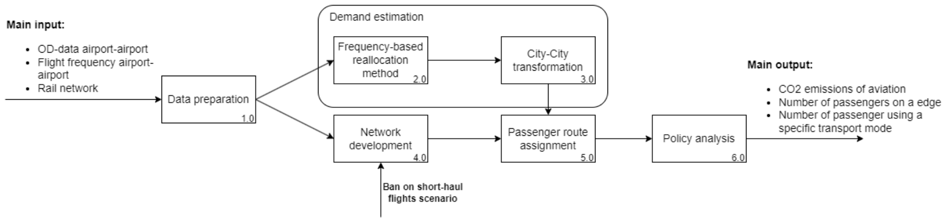



**Figure 3.7:** Global overview of the algorithm were a ban on short-haul flights is implemented

The same algorithm as in the base scenario is used to assess the effect of the ban. However, adjustments are made in the network design step to incorporate the ban. Several travel times in the network are set to zero to implement the ban, preventing the k-shortest path algorithm from using these edges. This section explains how, for each type of ban, it is determined whether the travel time of an edge is set to zero.

### 3.7.1. Distance based ban on short-haul flights

The distance-based ban is straightforward, which also makes it easy to implement. Section 3.2 discussed how different data was prepared. From this preparation, a matrix of distances between airports was calculated. This matrix forms the basis for this method. The used formula can be seen in Equation 3.18

**Distance-based ban calculations**

$$TT_{AB} = ((dis_{AB}/AVE_{ab}^{plane_{speed}}) + T_{taxi}) * Ban_{ab} \tag{3.18}$$

$$Ban_{ab} = \begin{cases} 1, & \text{if } dis_{AB} >= Dis_{ban} \\ 0, & \text{otherwist} \end{cases} \tag{3.19}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}$ | Total flight time between airport A and Airport B in hours |
| $dis_{AB}$ | Distance between airport A and airport B in km |
| $Dis_{ban}$ | Distance based ban value in km |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |

The formula consists of two parts. The first part, as explained earlier in the basic formula, calculates the travel time between two airports. The second part determines whether the specific flight is subject to a ban. This is assessed by examining the distance between the two airports.

### 3.7.2. Time based ban on short-haul flights

The time-based ban is more complicated to calculate. This is because the ban depends on a potential train route. Therefore, to determine the ban, possible alternatives must first be considered. This will be done using the Dijkstra shortest path method to find the fastest route through the HSR network. This will only be applied when a flight departs from a city within the EU and arrives in another city within the

EU.

Earlier in this report, the discussion focused on airports with HSR stations and those without. Theoretically, a passenger departing from an airport without an HSR station would have no access to the HSR network. This situation puts airports with HSR stations at a disadvantage compared to those without. To mitigate this issue, a decision was made to link airports within 50 km of the city centre. This means the shortest path method will be calculated from one city centre to another.

**Time-based ban calculations**

$$TT_{AB}^{Plane} = ((d_{AB}/AVE_{AB}^{plane_{speed}}) + T_{taxi}) * Ban_{ab} \tag{3.20}$$

$$a_{AX} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_A)\cdot\cos(\phi_X)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{3.21}$$

$$a_{BY} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_B)\cdot\cos(\phi_Y)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{3.22}$$

$$d_{AX} = 2r\cdot\arcsin\left(\sqrt{a}\right) \tag{3.23}$$

$$d_{BY} = 2r\cdot\arcsin\left(\sqrt{a}\right) \tag{3.24}$$

$$dis_{AX} = \begin{cases} 1, & \text{if } d_{AX} \text{ <= 50} \\ 0, & otherwise \end{cases} \tag{3.25}$$

$$dis_{BY} = \begin{cases} 1, & \text{if } d_{BY} \text{ <= 50} \\ 0, & otherwise \end{cases} \tag{3.26}$$

$$Ban_{AB} = \begin{cases} 1, & \text{if } TT_{X_AY_B}^{HSR} \text{ >= } T_{ban} \\ 1-(d_{AX} * d_{BY}), & \text{otherwist} \end{cases} \tag{3.27}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}^{Plane}$ | Total flight time between airport A and Airport B in hours |
| $TT_{X_AY_B}^{HSR}$ | Travel time between connected city x to airport A and connected city y to airport B |
| $dis_{AX}$ | 1 if city X is in the service area of airport A |
| $T_{ban}$ | Time based ban value in hours |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |
| $\phi_1, \phi_2$ | Latitudes of the two points (in radians) |
| $\Delta\phi$ | $\phi_2 - \phi_1,$ difference in latitudes |
| $\Delta\lambda$ | $\lambda_2 - \lambda_1,$ difference in longitudes |
| $r$ | Radius of the sphere (e.g., Earth's radius) |
| $a_{ax}$ | Intermediate value in the Haversine formula between airport a and city x |
| $d_{ax}$ | Great-circle distance between airport a and city x |

To calculate the new times between airports, it is first necessary to identify which airports and cities are associated. This is done using the Haversine formula (Equation 3.21,3.23,3.22 and 3.24). After calculating the distances, it is necessary to verify whether the airport and the city are linked. This step is addressed in Equation 3.25 and 3.26. Once these steps are completed, it is possible to check whether a ban is in force on the specific route. The variable $Ban_{AB}$ is determined by first calculating the variable $TT_{A_XB_Y}^{HSR}$ using the Dijkstra shortest path method. If the fastest time between cities exceeds the ban, the variable $Ban_{AB}$ will be set to 1. If the time is shorter than the ban, it will check whether the airports are connected to the cities. If both airports are connected, $Ban_{AB}$ will have a value of 0; if a combination of city and airport is not connected, this value will be 1.

# 4

# Specification of Model Inputs and Parameters

Chapter 3 explained the methodology for this study. To run the algorithm, various data are needed. Some parameters have already been briefly covered, while others are still missing. This chapter will discuss the different data required for the study and its sources. The structure of this chapter begins with a list of the hubs considered for this research, followed by information about the data related to the hubs. Next, the parameters for demand estimation will be discussed. This will be followed by an explanation of the input data that is removed from the study and a brief description of how the HSR network is structured. The chapter will conclude with the different scenarios of the ban on short-haul flights that will be researched in this study.

## 4.1. The study's hubs and their data

This section will first briefly discuss the selected hubs for this study and then explain the data collected on them.

### 4.1.1. The selected hubs in this study

Arround of Europe there are a lot of different airports, The policy of the flight ban will be performed by the European union, that means that all Eurean union members will be impacted by this policy. To get a good idea of what effect the ban will have around Europe, it is important to give all European union members a big hub. For this reason there is chosen to include the biggest airport of all the different European Union countries.

For the selection of the different hubs, one of the two requirements for determining if an airport is a hub was considered, namely connectivity. This was assessed using ACI (2024) report, which ranks the top 20 airports with the best connectivity in Europe. The report includes several lists, including one for hub connectivity, distinguishing between large, medium, and small hubs. From each list, the airport with the highest connectivity in each country was selected, regardless of whether it serves as a home base for an airline.

The report revealed that more than one major airports are located in some European countries, which are recognized as hubs with good connectivity. Since these hubs are significant to the study, they were included. Spain has two hubs: one in Barcelona and one in Madrid. Germany also has two hubs, in Munich and Frankfurt. Additionally, the UK has three hubs: London Heathrow, London Gatwick, and London Stansted. Notably, no major airline has a home base at London Stansted; however, it was included in the report because other airports with worse scores were also considered.

In addition to the list of hubs, their locations were verified using Google (2025). To provide a clear picture of the different hubs, a map has been created in Figure 4.1, which also indicates whether a hub has an HSR station. Each hub was individually checked for an HSR station using Google (2025) and

Interrail-Eurail (2024). The figure shows that Budapest Airport has an HSR station, which is located just outside the airport. However, since there is a 24/7 shuttle to the HSR station, it was noted that Budapest Airport has an HSR station. This isn't done for other airports because HSR stations are often located much farther from the airport. Also Athens has a HSR station in this study. In reality, only regular trains depart from Athens airport. However, as the study extended an HSR line to Athens, it was decided to also assign the airport an HSR station since they are already connected on the same line.

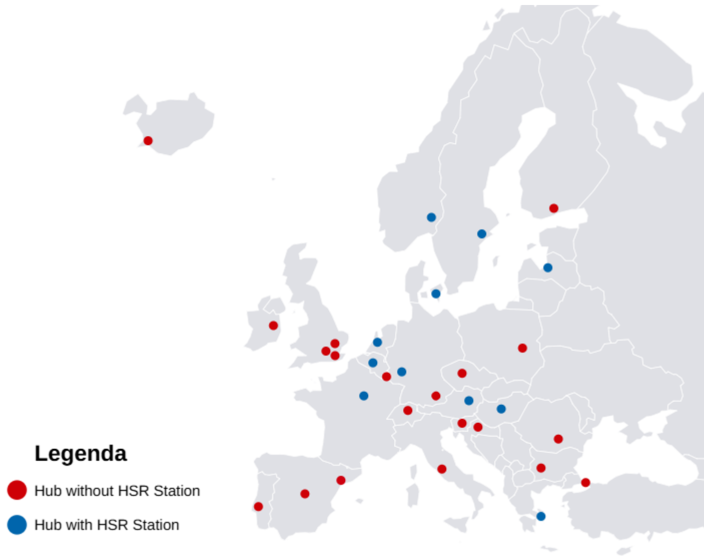



**Figure 4.1:** An overview of the different hub locations and their HSR station availability

## 4.1.2. The specific data that is needed from the different hubs

Above is explained which hubs have been selected for this study. Different forms of information are needed for the various hubs, comprising three elements. The first is the transfer percentage; this information is required to adjust the airport data for transfer passengers. The transfer rate is presented as a percentage, representing the average number of passengers making a transfer at the specific hub. The second relevant form of data is whether an airport has an HSR station. This was investigated using Interrail-Eurail (2024). The map was used to determine which airports have a station or are in the process of constructing one. The last required form of information is the transfer time between trains and planes. This data is based on the transfer times explained in Appendix F. The different data for each hub can be found in Table 4.1 and Table 4.2.

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source transfer-ratings |
|---|---|---|---|---|---|
| Amsterdam (Schiphol) | EHAM | 36.3% | Yes | 75 min | Schiphol Airport (2024) |
| Brussels | EBBR | 14% | Yes | 75 min | Brussels Airport (2023) |
| Munich | EDDM | 45% | No | 90 min | Munchen Airport (2024) |
| Sofia | LBSF | 0.9% | No | 90 min | Sofia Airport (2023) |
| Zagreb | LDZA | **0.9%** | No | 90 min | Based on Sofia airport |
| Vienna | LOWW | 22.41% | Yes | 75 min | Flughafen Wien (2024) |
| Prague | LKPR | **0.9%** | No | 90 min | Based on Sofia |
| Copenhagen | EKCH | 21.67% | Yes | 75 min | Copenhagen Airport (2024) |
| Helsinki (Finavia) | EFHK | 10.92% | No | 90 min | Finavia (2024) |
| Paris (Charles de Gaulle) | LFPG | 20% | Yes | 75 min | Groupe ADP (2024) |
| Frankfurt (Fraport) | EDDF | 50% | Yes | 75 min | Fraport (2024) |
| Athens (Athens Intl) | LGAV | 18.6% | Yes | 75 min | Athens International Airport (2024) |

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source |
| --- | --- | --- | --- | --- | --- |
| Budapest (Ferenc Liszt) | LHBP | **0.4%** | Yes | 75 min | Based on NACO |
| Reykjavik-Keflavik | BIKF | 27% | No | 90 min | Isavia (2024) |
| Dublin | EIDW | 3.4% | No | 90 min | DAAgroup (2024) |
| Rome-Fiumicino | LIRF | **22.41%** | Yes | 75 min | Based on Flughafen Wien (2024) |
| Riga | EVRA | **0.9%** | Yes | 75 min | Based on Sofia |
| Luxembourg | ELLX | **0.9%** | No | 90 min | Based on Sofia |
| Warsaw-Chopin | EPWA | 26% | No | 90 min | Warsaw Chopin Airport (2024) |
| Lisbon | LPPT | **20%** | No | 90 min | ACI (2024) based on Rome and Athens airport |
| Bucharest-Henri Coandă | LROP | **0.9%** | No | 90 min | Based on Sofia |
| Ljubljana | LJLJ | **0%** | No | 90 min | Based on the possible routes and airlines |
| Madrid | LEMD | **33%** | No | 90 min | Based on NACO |
| Stockholm-Arlanda | ESSA | **7%** | Yes | 75 min | Based on 0.5 * Brussels airport |
| Barcelona | LEBL | **4.9%** | No | 90 min | Based on NACO |

**Table 4.1:** Information about major hubs in the European Union

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source |
| --- | --- | --- | --- | --- | --- |
| Istanbul | LTFM | **58.1%** | No | 90 min | Based on NACO |
| Oslo | ENGM | **13%** | Yes | 75 min | Based on NACO |
| Zurich | LSZH | 29.7% | No | 90 min | Zurich Airport (2024) |
| London Gatwick | EGKK | **14%** | No | 90 min | Based on Brussels |
| London Heathrow | EGLL | **24.6%** | No | 90 min | Based on NACO |
| London Stansted | EGSS | **7%** | No | 90 min | Based on Stockholm airport |

**Table 4.2:** Information about major hubs outside the European Union (highligted numbers are estimated)

Searching for the data was quite easy for several airports. The problem was that not all airports made their transfer data public. Therefore, some data were estimated. The estimated data are bolded in Table 4.1 and 4.2.

The estimated transfer times are estimated based on other airport types. The first one is for Small type of airports with a lot of low-cost carriers. These airports aren't having much destinations and doesn't have a big carrier that use the hub and spoke principle stationed at the airport. They have one till five long-haul routes arriving at the airport. These airports are based on Sofia airport, because Sofia airport is very much alike the other airports and had published their transfer ratings. Because this The airports based on these estimations are:

- Riga
- Luxembourg
- Zagreb
- Bucharest-Henn Coand
- Prague

The smallest airport in this study is Ljubljana Airport. This airport has only a few routes, including one intercontinental flight. Additionally, there is no airline with a hub-and-spoke strategy that operates at Ljubljana Airport. Therefore, it is decided that this airport is a hub, even when there are currently no passengers transferring at this airport. The decision to make this airport a hub is based on the need for each EU country to have a hub, and this is the largest airport in Slovenia.

Medium airports are similar to small airports, but they differ in that they have a home carrier that is part of an alliance that includes major airlines. They often serve a few intercontinental destinations operated by hub carriers from other hubs. The hub is also among the top 20 for hub connectivity in Europe ACI (2024). While there was already a lot of data available, the only issue was with Stockholm-Arlanda airport. For this reason, the transfer rating for this airport is based on Brussels. Because the routes of these two airports are very similar, the transfer rate will also likely be very similar.

The major hubs around of Europe are harder to estimate what transfer-rate they have. Take for example the difference between Paris (Charles de Gaulle) and Frankfurt airport. In theory they are both major hubs and are both the home base of a major airline in Europe. However there can be seen in Paris (Charles de Gaulle) much less transfer passengers than in Frankfurt. One possible explanation could be that Frankfurt isn't a destination that has a high attraction rate. Where Paris is a major city in Europe that has a big tourism market. This could result that Paris is a final destination for a lot of people. The problem this poses is that it makes it difficult to provide an accurate estimate of the number of passengers. Therefore, an analysis was conducted by NACO on the number of transfer passengers.

## 4.2. Parameters for the demand estimation

In demand forecasting, several variables are essential for accurately estimating demand. Some have already been addressed in this chapter and chapter 3, but important elements are still missing. This section will first discuss the final parameters required for reallocating airport data, followed by a brief overview of the additional data needed for city-to-city reallocation.

### 4.2.1. Parameters for the Dynamic Restricted Area method

The Dynamic Restricted Area method is necessary to identify illogical interchanges for passengers. After a passenger selects a route, circles are utilized to pinpoint these illogical interchanges. Table 4.3 offers an overview of the various degrees used in this study. The table first displays the type of flight the passenger took to the hub, followed by the possible transfer flight types the passenger can take. This combination yields a specific degree that indicates the size of the prohibited area deemed unrealistic for transfers. Appendix C provides an example of how to read and apply this table.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

**Table 4.3:** Restricted areas after different flights

Besides consulting with experts, the world map was used to assess the impact of his circle on routes. Several examples were considered, such as a flight from South Africa to the Netherlands. After this flight, it is reasonable to assume that the passenger will not fly back to Central and Southern Africa. However, for medium-haul flights, it remains logical that the passenger might continue from the Netherlands to Dubai. In the case of short-haul flights, everything aligns, as a short flight following a long one does not significantly affect the passenger. This reasoning was applied repeatedly from different options. By doing this several times, the values of the circles could be verified to ensure they did not produce unusual results.

### 4.2.2. Final parameters for the City-to-City allocation

The first step of the City-to-City allocation method was to determine the utility of different flight paths. This step comprised four elements. The first was the average waiting time for a passenger, which was approximated by considering the frequency of aircraft across different routes. To calculate this waiting time the displaced scheduled time was used. For the transfer waiting time is also the displace schedule time used. The displaced scheduled time was calculated using Equation 4.1.

$$DP_i = \frac{1}{4} \times \frac{365 * 24}{F_i} \tag{4.1}$$

| Variable | Meaning |
|---|---|
| $DP_{ij}$ | Displaced schedule time for a passenger that wants to fly between airport i and j |
| $F_{ij}$ | Annual frequency of flights between airports i and j |

In addition to the displaced schedule time, access and egress times were also considered; these values are derived from the travel time between the airport and the city, which are based on the times explained in Appendix F. The final parameter required for the utility function is the determination of whether a passenger must cross an international border. The data regarding the cities and airports indicate the country in which each is located.

The alphas used for the MNL model, shown in Table 4.4, are based on Grolle (2020) study. These alphas are relevant to this study because the studies share similar objectives. Moreover, the same variables are used in this study and that of Grolle (2020).

| Alpha Acces and Agress time | Alpha border crossing | Alpha Displaced schedule time | Max iterations |
|---|---|---|---|
| -0.4 | -0.04 | -0.56 | 10,000 |

**Table 4.4:** Parameters City-City transformation

The final key data for the model pertains to various cities. This information was partly sourced from Grolle (2020) and supplemented through desk research (Google (2025)). The population of a city takes into account both its size and the area it serves, reflecting the entire urban area rather than just the city center. The data is available in Appendix G.

The remainder of the demand estimation relies on data generated by the model. The location of the different cities can also be found in Appendix G and is found by desk research (Google (2025))

## 4.3. The correction of input data

The study used large data files from Eurostat (2025), which contain passengers carried on the routes flown from major hubs in Europe. The issue with the data is its size, leading to long calculation times. Therefore, unnecessary data was removed from the model for several reasons. The list of removed airports can be found in Appendix D.

The first reason airports have been removed is the small flights between Turkish cities. These airports only had flights departing to Turkey. As the study focuses on the impact on the European Union, data from these flights are not relevant. Additionally, the ban will have no impact on these trips, making no difference in the final data. Therefore, it was decided to remove these domestic flights. This decision was also made for international flights from airports that only travelled to Turkey, as they are irrelevant for the same reason.

The issue with the data from the UK is that it dates back to 2019, while the rest is from 2023. This is due to the UK leaving the European Union in 2020, which meant it was no longer required to share this data. Additionally, there were routes that exclusively departed from UK airports. These flights, like those to Turkey, will have no impact. Consequently, it was decided to exclude these flights from the study, leading to the removal of several airports. The same is for airports in Finland that are only used for domestic flights.

The study chose not to include all cities in Europe. Including them would make the model too large, and it is questionable whether this would significantly affect the results. Consequently, some airports are not linked to cities. To avoid losing passengers as a result, the decision was made to remove the airports that could not be linked from the network. These airports are often located on islands or near cities that do not yet have an HSR station.

Finally, there was an issue with Soekarno-Hatta International Airport in Indonesia. After reviewing the data, it was found to be incorrect. A comparison with other airlines revealed that there were more flights arriving from different cities to this airport, while the data indicated only a flight from Turkey. Therefore, it was decided to remove this airport, as its inclusion would distort the results, and removing it will have no impact on the findings.

## 4.4. Emission parameter

To calculate average emissions per passenger, several choices were made. First, an average figure for all flight types was used. chapter 1 shows that long-haul flights emit more than short-haul flights. However, the number of passengers on short-haul flights is expected to fluctuate significantly, while this effect will remain small for long-haul flights. This study primarily focuses on the impact of the ban rather than on precise predictions of the outcomes if the ban is implemented. Therefore, an average number of CO2 emissions per passenger per kilometre was chosen.

The average emissions per passenger per kilometre are based on the emissions of a Boeing 737-400, the most common aircraft type in 2008. This year was chosen due to the availability of data. This narrow-body aircraft has smaller engines and is primarily used for short-haul travel. The selected emission value is 115 g/passenger/km (Carbon Independent (2025)). Note that current aircraft are much cleaner due to innovations in recent years. But this study does not aim to determine an exact emissions figure and focuses solely on comparing CO2 emissions from aviation, after a ban is implemented. Therefore, the value of this data is not crucial for the conclusions.

## 4.5. The design of the HSR network

Looking at Figure 2.5 from chapter 2, it is noticeable that the European HSR network is not yet fully complete. Additionally, several important connections remain unestablished. Including this network in the study is therefore complicated. This situation necessitates examining the current state of each line and its future prospects.

To maintain an optimal HSR network, it was decided to assign HSR stations to all cities in Europe that were included in the model. The cities included in this study are listed in Appendix G. To design a realistic future HSR infrastructure, the developed HSR network from Grolle (2020) was adopted. Grolle (2020) study examined how to optimally roll out the HSR network in Europe to effectively connect European cities. However, Grolle (2020) study did not consider HSR stations at airports. Therefore, Interrail-Eurail (2024) was consulted to determine which airports are accessible by some form of train. If an airport has a station, but no HSR trains currently run on it, the study opted to upgrade the lines and classify them as HSR stations. More cities have been included in this study than in Grolle (2020) work to ensure they have HSR connections. Interrail-Eurail (2024) was referenced to identify which cities are connected by train; if there is a connection, it is considered an HSR connection in the model. Figure 4.2 shows the network used in this study. Cities are indicated in blue, and stations at airports in red.

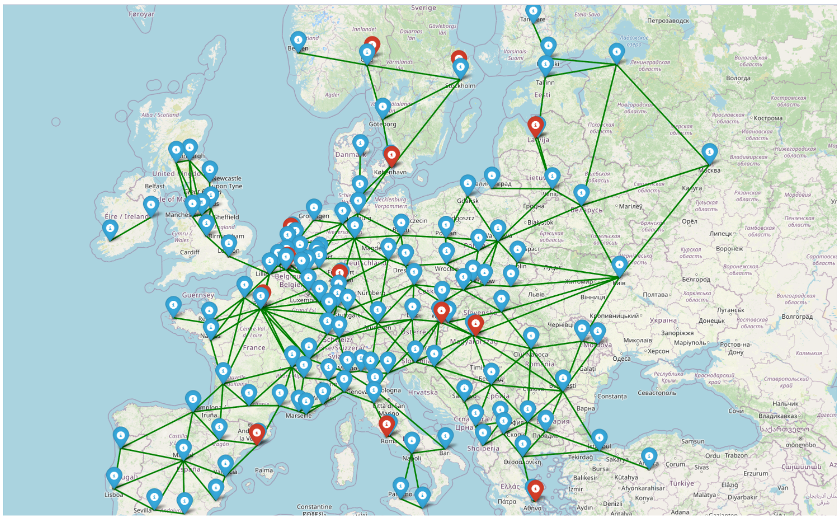


**Figure 4.2:** The HSR network that is used in the Algorithm

## 4.6. Scenario's of the ban on short-haul flights

Currently, several companies and countries have implemented bans on short-haul flights. It is particularly striking that countries impose relatively small bans, while companies opt for more drastic measures (Wikipedia (2025)). The choice of different policy scenarios is based on the current actions taken by companies or countries. The chosen policy scenarios can be found in Table 4.5. The aim is to make both types of bans roughly equal. This has been done to ultimately compare which type of ban will be the most effective.

| Policy scenario's | Low | Middle | High |
|---|---|---|---|
| Time-based | 2.5 hours | 6 hours | 14 hours |
| Distance-based | 250 km | 750 km | 1500 km |

**Table 4.5:** Different policy scenarios

Starting with the high scenario, the aim is to significantly intervene in the aviation market. This scenario proposes a complete ban on short-haul flights for both types of bans. Figure 1.2 noted that short-haul flights account for about 24% of total CO2 emissions. A complete ban on short-haul flights with the current HSR network should theoretically reduce emissions by at least 20%. This scenario allows to assess what impact a full ban has on the base scenario, where a full functional HSR network is implemented. With a time-based ban, CO2 reductions will properly be slightly lower than with a distance-based ban, as more routes are permitted under the time-based ban to consider possible alternatives.

For the middle scenario, its based on the study of Adler et al. (2010). According to a study by Adler et al. (2010), his research found that trains are faster than planes till a distance of 750 km. This distance is therefore an interesting benchmark. According to the theory that people always choose the fastest route, this suggests that at this point people should chose 50/50 between air or rail. The question then arises as to whether this holds true if passengers can also fly around the ban. So their can be expected that this scenario is one of the most optimal formats for the ban. The time-based ban will also represent a distance of 750 km. As this means that it would take approximately 6 hours for a person to cover 750 km. The six hours is found by desk research (Google (2025)) different routes, and look how long this takes.

The last and lowest scenario is based on the current policy in France (de Weert (2022)). France has enacted a law, approved by the EU, that bans flights within 2.5 hours of train travel. The purpose of this ban is to eliminate flights within an EU country, as these can be easily replaced by other modes of transport. According to Adler et al. (2010), high-speed rail (HSR) should be significantly faster over this distance. However, the ban can be relatively easy to circumvent. Therefore, it will be interesting to investigate whether this ban will ultimately achieve its intended effect. Desk research indicates that the distance-based ban in this scenario should be 250 km Google (2025).

# 5
# Validation and verification of the model

Now that the algorithm has been developed and the necessary data had been explained, it is time to assess the effectiveness of this model. This chapter will explore this verification process in detail. It will begin with a theoretical evaluation of the algorithm. Next, a small case study will be executed to verify if the algorithm works, and also to get some insides in the working of some variables. These two points will be used to discus the algorithms strengths and weaknesses.

## 5.1. Theoretical evaluation of the algorithm

This research has presented an algorithm with different methods, some are based on proprietary literature. This section will discuss the evidence from previous studies and explain why these methods are also effective in this study.

### 5.1.1. Theoretical working of the demand estimation

The demand estimation algorithm is divided into two parts. The first part addresses the reallocation of passengers in the Eurostat data. Previous literature did not provide a method for this. Consequently, a new method was developed to explain, in a straightforward manner, passengers' transfer choices. Due to these choices, it is not possible to validate this method through existing theory. The same problem arises when checking the degrees for the Dynamic Restricted Area method. Since this method is new and does not appear in older literature, the values cannot be derived from previous sources. There was a discussion within RHDHV regarding the numerical data; however, the experts also encountered challenges in logically validating these figures. The long- and short-haul flights seemed reasonably accurate, but the medium-haul flights proved difficult. In conclusion, validating the correction of Eurostat data cannot be based on theory. It will therefore have to rely on the results obtained from the model.

After correcting the Eurostat data, an attempt was made to transform the Airport data to City-to-City data. This was based on Grolle (2020) research, which also draws on other studies. Because the method is used in previous studies, it can theoretically be said that the theory used should be effective, although several adjustments were made in the implementation of the method. This research included transfer passengers, and the method was also applied to cities outside Europe. Ultimately, however, the model's functionality has not changed; only different choices have been made. Thus, it can be assumed that this part of the method is representative of reality. However, it is still a model, and a model is generally incorrect.

### 5.1.2. Theoretical working of the passenger assignment

The passenger assignment consisted of two parts. The first part focuses on creating the network, which the second part uses to find routes. In this phase, various travel time choices were made for completing a route. Average speeds were determined from existing literature, but their impact on the model is hard to predict due to the differing sources of these values. Therefore, later in this research, a case study will be used to better understand the effects of this data.

When the ban is implemented in this step, it can be done in two ways. The first type of ban is distance-based and is straightforward, requiring no additional parameters. Validation is not relevant for this part; however, verification is important and will be addressed later in the chapter.

However, for the time-based ban, it is crucial to ensure that everything functions correctly. This is because the operation of this ban is based on city centres, which are linked to airports. This complicates the process of verifying whether the tolerance level is adequate and meets expectations. There can also be significant differences when comparing various airports and their distances to city centres. For instance, Amsterdam and Schiphol Airport are only 18 km apart, while London is 64 km from London Stansted. To check if the ban is working a verification is needed, this will be done by running a small case study.

In passenger route assignment, the key parameter is the number of iterations the k shortest path algorithm can utilize. Theoretical information on a specific value for this purpose is limited. Therefore, the case study is used to demonstrate whether the chosen value yields the desired results.

In the k shortest path method, several penalties have been added to enhance realism. These penalties involve various assumptions that may differ from one airport or situation to another. Consequently, it is theoretically challenging to demonstrate that these figures accurately represent reality and meet expectations. However, ultimately the numbers are based on real-world data. To ensure that the penalties align with expectations, further investigation will be conducted in the small model.

Using the routes, the probability of someone choosing a specific option is considered. This is calculated using the Random Regret method from Donners (2016) study. He also uses the betas included in this study; therefore, it can be theoretically established that this method and the numbers should give a realistic result.

## 5.2. Case study

Broadly speaking, the method can be validated through the literature. However, this is often trickier with the different numbers used. Additionally, there are new elements that have not been previously described. To verify and validate these elements, a small case study was developed, as the real model is too large to run multiple tests on. Several experiments can be conducted with this case study to gain a better understanding of how the model functions.

The case study's detailed explanation can be found in Appendix E. In Table E.1 is a list of the different routes that were used in the case study, this is in the same format as the input data form Eurostat (2025). But only a select group of airport combinations is chosen to implement in the case study. Additionally, all cities included in the large model have been added. One effect of this is that there will be a lot more train travel because a lot of the destinations do not have an airport. As a result, relative to Airport and city data, many passengers will be lost. This is not an issue for validation, as the city-to-city method will not be validated with this small run.

Using this case study, various aspects will be assessed. The evaluation will focus on two primary areas: the operational functionality of the model and the extent to which its outputs accurately reflect real-world conditions. The validation and verification process will examine the following components. Initially, it will look at the Dynamic Restricted Area and Frequency-based reallocation method. After it will verify whether the ban is implemented correctly. Subsequently, the base scenario's results generated by the model will be presented to determine their alignment with anticipated outcomes. Following this, various penalties will be verified. Next, the effect of the number of iterations will be validated. Also an analysis of the k-value will be undertaken to assess its appropriateness in the context of the model. Lastly, there will be looked at the HSR network and how good this represents the real-world.

### 5.2.1. Verification of the airport reallocation method

A new method has been designed to correct the input data form Eurostat (2025). Important variables from this method are the degrees from Table 4.3, which are used for the Dynamic Restricted Area. By adjusting various variables, the impact on different routes is examined to determine whether it is justified. The routes were selected between Abu Dhabi and London City because these airports are not considered hubs by the model. In addition, the route from Schiphol to Abu Dhabi is also considered; because, Schiphol is considered as a hub within the study. Furthermore, Abu Dhabi is an airport outside Europe. The expectation of this test is that the number of passengers wishing to travel between two non-hubs will be significantly influenced by changes in the prohibited area indicators. Additionally, to verify the effectiveness of the frequency-based reallocation method, the direction of routes to the hub must always be negative relative to the input. If this occurs, it indicates that the method is functioning as intended. The results of this verification are shown in Table 5.1.

| Scenario | Abu Dhabi International Airport → London City | % Difference with Output | Abu Dhabi International Airport → Schiphol | % Difference with Input |
|---|---|---|---|---|
| Input | 0 | - | 197310.00 | - |
| Output | 13264.80 | - | 166508.01 | -15.61% |
| After longhaul flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After longhaul flight transfer to short-haul flight 360° | 11898.84 | -10.30% | 164442.70 | -16.66% |
| After medium flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After shorthaul flight transfer to shorthaul flight 0° | 2764.97 | -79.15% | 164953.30 | -16.40% |
| After shorthaul flight transfer to longhaul flight 360° | 1365.962315 | -89.70% | 163563.5915 | -17.10% |

**Table 5.1:** Sensitivity analysis: Restricted area algorithm

As expected, Table 5.1 shows significant changes in the route between the two non-hub airports. The results indicate that the number of passengers is greatly influenced by changes in the prohibited area. This illustrates that the size of the prohibited area can significantly impact the results of this method. It is difficult to determine whether the chosen values reflect reality, given the results and the fact that not all routes were included in the case study.

Examining the route between Schiphol and Abu Dhabi, it is evident that all values relative to the input are negative. This indicates that fewer people travel on this route, reallocating to other routes. This suggests that the method is functioning as intended. In conclusion, the Frequency-based reallocation method performs as expected, but the Dynamic Restricted Area significantly affects the outcomes.

### 5.2.2. Verification of the ban on short-haul flights

This section will try to verify if ban is correct implemented in the model as in reality. To do this, several routes were examined within the small network to determine if these flights were banned. The results of this validation can be found in Table 5.2. Five different routes were plotted in the table; for each route, desk research (Google (2025)) was conducted to ascertain whether it was likely to be banned. It was then verified whether these routes were banned in the model. Table 5.2 shows that the model banned the routes identified for prohibition. This indicates that the algorithm accurately assigns bans to different routes.

| Route | Type of ban | Algorithm distance or travel time | Ban in reality | Ban in model |
|---|---|---|---|---|
| Schiphol Airport - Brussel Airport | 250km | 157.66 km | Yes | Yes |
| Schiphol Airport - Brussel Airport | 2.5 hours | 1.51 hour | Yes | Yes |
| Schiphol Airport - Josep Tarradellas Barcelona–El Prat Airport | 250 km | 1241.13km | No | No |
| Schiphol Airport - London Heathrow | 14 hours | 3.17 | No | No |

**Table 5.2:** Validation of the ban algoritme

### 5.2.3. Results from the case study

The following briefly discusses the case study results to evaluate the algorithm's results and their alignment with expectations. These results will also be used to verify if the penalties applied in the k shortest path method, are working as expected. Two indicators are considered: the first relates to $CO_2$ emissions of the alternatives, and the second focuses on passengers' transport choices in the different scenarios.

Figure 5.1 illustrates CO2 emissions from aviation from the case study. The analysis of the routes in the case study primarily focused on a few different routes. As could be expected the ban wouldn't influence much of these results. The changes in CO2 emissions are very small but show that the ban will effect the results of the model. Also the scenario's of the distance-based ban shown the same type of results in each scenario. There are no significant deviations in CO2 emissions across the scenarios with distance-based bans. The model indicates that the time-based ban more effectively reduces CO2 emissions, as expected, since it is more targeted. Additionally, the case study has limited options for rerouting, which explains the substantial difference in emissions changes between the distance-based and time-based bans.

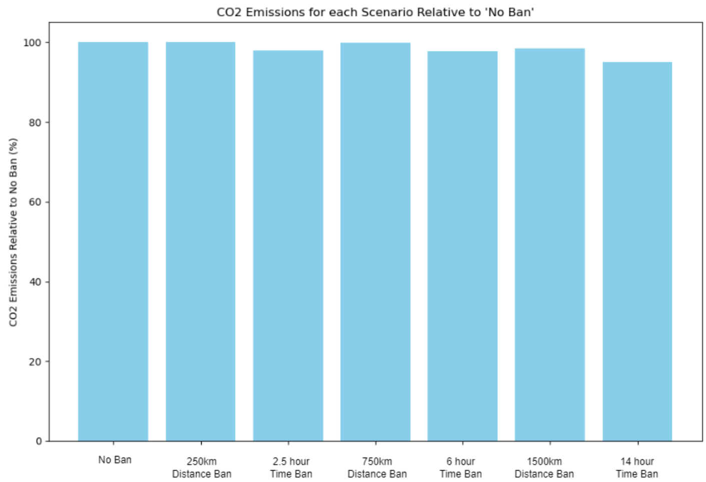



**Figure 5.1:** Result small validation: CO2 emissions for each scenario

The included routes, primarily consisting of European connections, were is expected to attract a significant share of passengers to rail travel. The algorithm was designed to utilize an efficient HSR network to capture a portion of these passengers, as many in the case study aimed to travel within Europe. It can be anticipated that the number of passengers choosing the rail alternative will be substantial. As the ban increases, it is expected that the number of passengers using HSR is going to rise, the results align with the expectations. However, it is noteworthy that there are few passengers with transfers, likely due to the limited number of available flights. As expected in the conceptualization, the increase in the ban will lead to a drop in the number of direct flights, while other alternatives will grow. This effect can be seen in the results shown in Figure 5.2. In conclusion, the algorithm does not produce any unexpected results, indicating that it is functioning as intended.

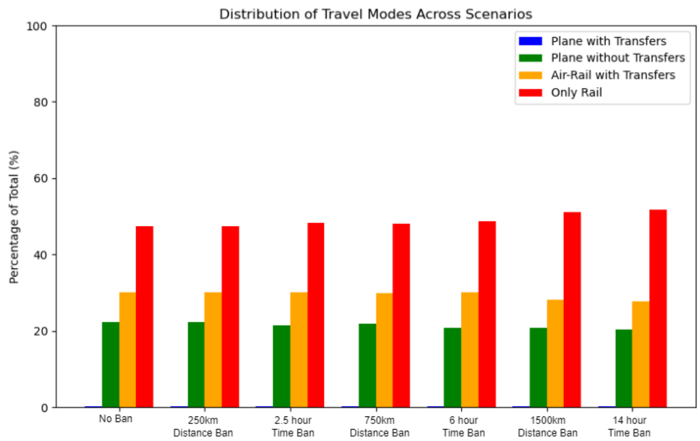



**Figure 5.2:** Result small validation: Distribution of passengers on transport modes

## 5.2.4. Verification of the different penalties

The model opted to use various penalties, implemented by adding different time penalties to specific choices during route design. To evaluate the effectiveness of these penalties, two were selected for assessment. This decision was made because the penalties are interrelated. The penalties that will be checked are the transfer penalties between two planes and the travel time by train to an airport. To check if the penalties are working, the results will be compared with Figure 5.2.

### Penalty for transfers on airports

To test whether the transfer penalty between two planes functions correctly, a small change was made to the code. If a passenger made a transfer, the time would decrease by 100 hours. Consequently, a significantly higher number of transfers should be evident in the results. However, due to the structure of the small case study, this will not reach 100%, as transfers are not possible for every route.

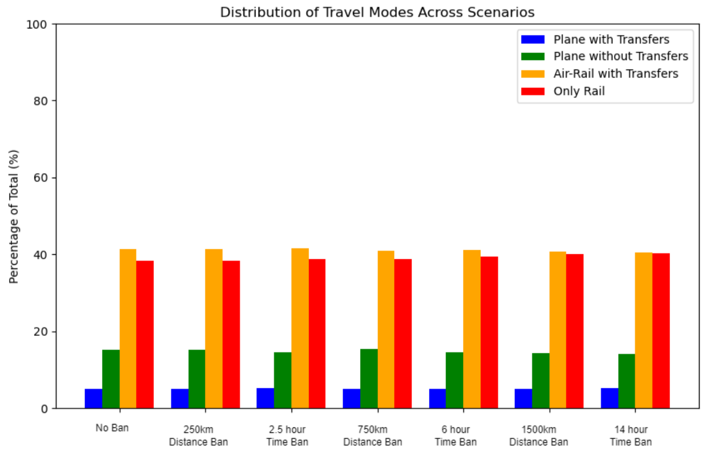



**Figure 5.3:** Proof of the effectiveness of the transfer penalty, if compared with Figure 5.2

Comparing Figure 5.2 and 5.3, Figure 5.3 shows that the number of passengers making a transfer increases when the penalty for a transfer is reduced by 100 hours, also the Air-Rail network is the biggest of the four alternative. This is because in the Air-Rail network there are properly also passengers with multiple flights. However, this increase is lower than expected, which can be attributed to the construction of the smaller model. Interestingly, the transfer passengers are those who have previously taken a direct flight or used a train. Overall, it can be concluded that this type of penalty functions as intended.

### Acces airport

To check whether entering airports is penalised with a waiting penalty, the penalty for passengers entering the airport after using the aircraft was examined. This penalty was increased from 3 hours to 20 hours. Due to this extreme effect, it is to be expected that passengers are less likely to want to enter an airport, resulting in them using the HSR more. Figure 5.4 shows the result of this research.

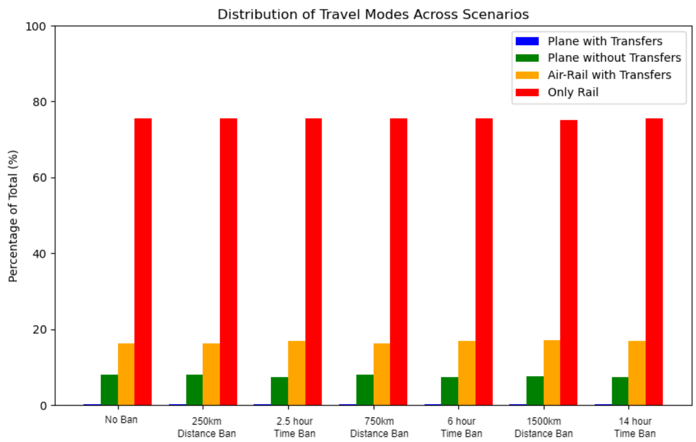



**Figure 5.4:** Proof of the effectiveness of the Rail-access penalty, if compared with Figure 5.2

When Figure 5.2 and 5.4 are compared, it is evident that the number of passengers using rail has increased significantly. This aligns with previously outlined expectations. This effect can be attributed to the fact that many trips start and end within the EU, making trains a viable option for shorter distances. These results indicate that the penalty for train use is effective.

### 5.2.5. Validation of the number of iterations

Several algorithms are used in this study. Because the shortest path algorithms can get stuck or repeat themselves, a maximum number of iterations was introduced. This allows for a maximum of x steps per route to find a faster option. The maximum is set at 1500 iterations in the base model, meaning that after 1500 steps, the model will proceed to the next route. To verify this number, runs with 500, 1000, 1500, 2000 and 2500 iterations were conducted in the smaller model to analyse sensitivity, the values from the base scenario are compared.

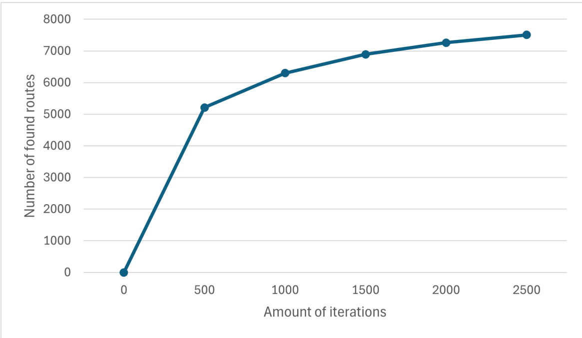



**Figure 5.5:** Increasing routes that are found by a higher number of iterations

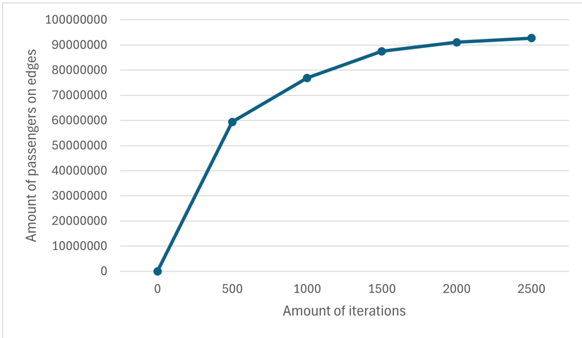



**Figure 5.6:** Stabilising number of passengers assigned to different edges with a greater number of iterations.

After running the model, the results of the first scenario, when no ban is active, were analysed. Two elements were extracted from these results. The first is the total number of routes identified by the algorithm. The second is the number of passengers assigned to the different edges. These results are shown in Figure 5.5 and 5.6 The number of passengers assigned to the edges exceeds the number of passengers included in the model because passengers are assigned multiple times to different edges.

With a higher number of iterations, the algorithm can identify multiple complex routes, ensuring an increase in passenger numbers across edges. This effect is clearly illustrated in Figure 5.6, which shows that between 500 and 1000 iterations, the number of passengers travelling across different edges rises dramatically. This indicates that more complex routes, consisting of multiple edges, are being found. However, from 1500 iterations onwards, the increase in passengers declines sharply. It becomes evident that new routes are still being discovered, but they are likely much slower than the existing routes. This is because the number of passengers across several edges no longer rises sharply, even though these routes are expected to be relatively complex. In conclusion, increasing the number of iterations reveals that, beyond 1500 iterations, new routes are still found in the network, but the number of passengers using these routes hardly increases.

The issue with the number of iterations is that as it increases, the time required for the model to run rises rapidly. It is therefore important to select an iteration number that estimates as much as possible without significantly increasing the algorithm's computation time. Figure 5.5 and 5.6 show that the number of new faster routes does not increase significantly beyond 1500 iterations. A choice can be made to continue increasing the number of iterations until the number of passengers found no longer rises, indicating that all the fastest routes have been identified. However, this may lead to excessively long search times for minimal improvements that lack significant impact. Thus, continuing to increase the number of iterations adds little value.

To further demonstrate that increasing the number of iterations has little impact, the effect of iterations on average speed is examined. The formula for this is presented in Equation 5.1. It consists of two parts. First, the average travel time between the two cities is calculated for each possible city combination by multiplying the travel time by the probability of choosing that route. Then, the distance between the two cities is divided by the average travel time. This process is repeated for all possible city combinations, and the average is taken to calculate the average speed between the two cities. This value can help determine whether faster routes are identified with more iterations. Figure 5.7 illustrates the different results. Despite continued increases in the number of iterations, the average speed between city pairs stabilizes around 1500 iterations, indicating that the fastest and most relevant routes have largely been identified by this point. It shows a local minimum at 1000 iterations.

$$\bar{v} = \frac{1}{|C|} \sum_{(i,j)\in C} \left( \frac{d_{ij}}{\sum_{k=1}^{r_{ij}} p_{ij}^k \cdot tt_{ij}^k} \right) \tag{5.1}$$

| **Variable** | **Meaning** |
|---|---|
| $\bar{v}$ | Average speed across all city pairs |
| $C$ | Set of all connected city pairs $(i, j)$ |
| $\lvert C\rvert$ | Total number of connected city pairs |
| $r_{ij}$ | Number of route options between city $i$ and city $j$ |
| $p_{ij}^k$ | Probability of using route option $k$ between city $i$ and $j$ |
| $tt_{ij}^k$ | Travel time of route option $k$ between city $i$ and $j$ |
| $d_{ij}$ | Fixed distance between city $i$ and $j$ (independent of $k$) |


**Figure 5.7:** Stabilising average speed with a higher number of iterations.

In conclusion, with a limited number of iterations, not all possible solutions can be found. Increasing the iterations beyond 2500 will enhance the number of routes identified, allowing the model to better predict complex routes. Regarding passenger allocation, it is evident that after 1500 iterations, relatively fewer passengers are found than before. When compared with the average travel time between cities, there is little improvement after 1500 iterations. This suggests that 1500 iterations may be a viable value to use in the study.

### 5.2.6. Validation of the k value

Within the algorithm, various routes are considered. In chapter 3, there was chosen to examine up to five different routes between cities. The question now is how significant the effect of these chosen routes is on the results. To assess this, different values for k and the total number of passengers assigned to the various edges are analysed.

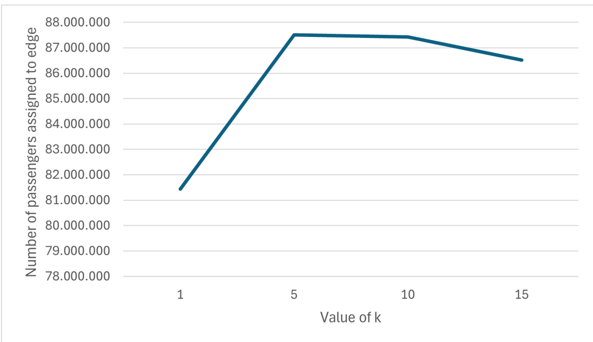



**Figure 5.8:** Validation of k-value with the number of assigned passengers

Looking at Figure 5.8, there is a noticeable difference between a k-value of 1 and 5. This indicates that significantly more complex routes are found, which is not necessarily a drawback. Comparing the k-values of 5 and 10, it can be observed that the increase in routes stabilises. While more routes are identified, this has little effect on the outcomes. Between k=10 and k=5, there is hardly any impact on the results. When the value of k is increased, the results may even decline. This can be attributed to the fact that more routes are selected, causing them to compete for the same passengers. As there is a maximum number of passengers that can be distributed among the different routes, an increase in the number of routes also leads to the selection of longer routes. These longer routes compete with one another for passengers, resulting in a total decrease and making the outcomes appear less reliable. Thus, choosing a k-value of five is not inappropriate.

## 5.3. Verification of the HSR network

As an alternative to the aircraft, this model has opted to implement an HSR. The HSR network used for this purpose has been optimised by the model. In addition to this optimisation, it has been decided not to use lines on the HSR network. This ensures that the model is not restricted to specific routes and passengers can make free choices about which directions they want to travel by train. The question now is what effect this has on the model and whether it can be considered reliable. This question was addressed by searching Google Maps (Google (2025)) for the fastest public transport route between cities. The algorithm was then used to determine the predicted travel time for the route. The results of this study can be found in Table 5.3.

| HSR-Route | Real time (hour) | Model time (hour) | Percentage difference |
|---|---|---|---|
| Amsterdam-Brussel | 2.3 | 1.88 | -18.26% |
| Amsterdam-Barcelona | 11.43 | 9.05 | -20.82% |
| Rome-Barcelona | No train option (17.41 bus option) | 7.21 | -58.59% |
| London-Amsterdam | 4.75 | 3.96 | -16.63% |
| Paris-Lille | 1.03 | 1.26 | +22.33% |
| Paris-Amsterdam | 3.38 | 3.76 | +11.24% |

**Table 5.3:** HSR travel times real vs model outcomes (Google (2025))

Looking at Table 5.3, it is evident that the algorithm estimates routes between different cities is not the same as in reality. In Western Europe, where better connections between countries often already exist, the HSR is estimated quicker or slower depending on the route. This variation in speeds can be explained by how Europe has built its railways, as each country is individually responsible for its infrastructure. Furthermore, this model does not account for the differing layouts of train lines. From a passenger perspective, several factors contribute to different journey times in the model compared to reality. Specifically, the model includes an average waiting time at each edge to account for train braking and transfers. However, this does not always reflect real-life experiences. Passengers often need to change trains more frequently and for longer durations. Additionally, in Paris, passengers regularly have to switch between stations before continuing their journey. Consequently, this results in different journey times than the model suggests.

The model does not estimate the routes 100 per cent accurately, which is an important aspect to consider in the results. The number of routes that are faster in reality than those estimated by the model is relatively low. Therefore, it is expected that more people will ultimately prefer trains in the final results. This is because the HSR network considered in this study operates relatively optimally, enabling trains to compete more effectively with air travel than in reality. As a result, more people are allocated to the HSR than would be the case in reality.

# 6 Results

This chapter will present the study's results. It will begin with an explanation of the base alternative results. Followed by an explaination of the passenger choices, what result in an impact by each scenario on CO2 emissions. Finally the impact of the different hubs will be explained.

## 6.1. Results of the base scenario

Due to the absence of reference data, a base case was developed. This scenario can be compared with various scenarios where a ban on short-haul flights is in effect. It can also be used to evaluate the impact of model choices. The assessment of the base scenario considers the mode choices made by passengers found by the model, with results shown in Figure 6.1. The mode choices are divided in three possible options: train, plane or Air-Rail.

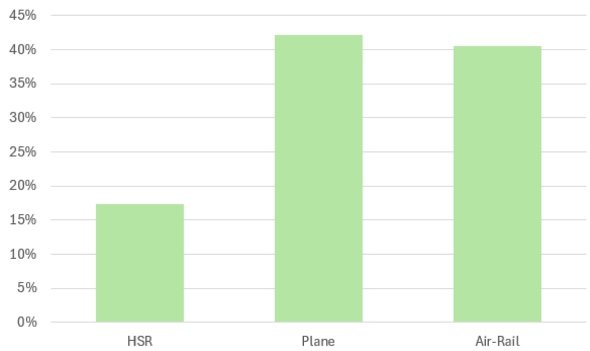



**Figure 6.1:** The choices of the passengers in the base scenario were no ban is applied.

Looking at Figure 6.1, the most important fact is that a group of passengers is already attributed to the HSR, which is remarkable because the input data consists of 100% air passengers. As discussed earlier, this can be explained because this study uses a well-functioning HSR infrastructure. Suggesting that with a full functional HSR infrastructure a large group of people will already obt for a HSR alternative.

The model did not include all forms of travel. For instance, it excluded passengers traveling from outside Europe to another destination outside Europe who currently use a European hub. The proportion shown in Figure 6.1 consists solely of passengers traveling to or from a European destination. Consequently, this study did not compare CO2 emissions from aviation between reality and the baseline scenario. With the rise of high-speed trains (HSR), it can be suggested that CO2 emissions from aviation will be lower in the baseline scenario than in reality. This should be considered when comparing the ban with the baseline.

The high share of HSR use may also be attributed to the model's focus on travel time and some comfort, without factoring in travel costs, which could influence the results. Since travel costs were not analysed, it is unclear whether HSR use is overestimated or underestimated in the baseline scenario with a fully functioning HSR network. If the travel costs for both modes of transport are equal it wouldn't influence the results very much, but this research didn't look at the different costs for transport

With the improved HSR network, a significant number of passengers are already choosing the Air-Rail network. The results provides insight into the Air-Rail network's impact and demonstrates its competitiveness with air travel, given a strong HSR infrastructure. But travel costs are not included in the model, and these could change the results of the base scenario.

## 6.2. Passenger choices compared to the base scenario

The study compared six different bans on short-haul flights with the base scenario, investigating their impact on passenger behaviour. In each scenario, the ban is implemented alongside a well-functioning HSR infrastructure in Europe. The results focus on overall modal choice and the effects on direct and transfer passengers, as illustrated in Figure 6.2 and 6.3. All scenarios will be analysed individually using these two figures to evaluate what choices passengers made compared to the base scenario.

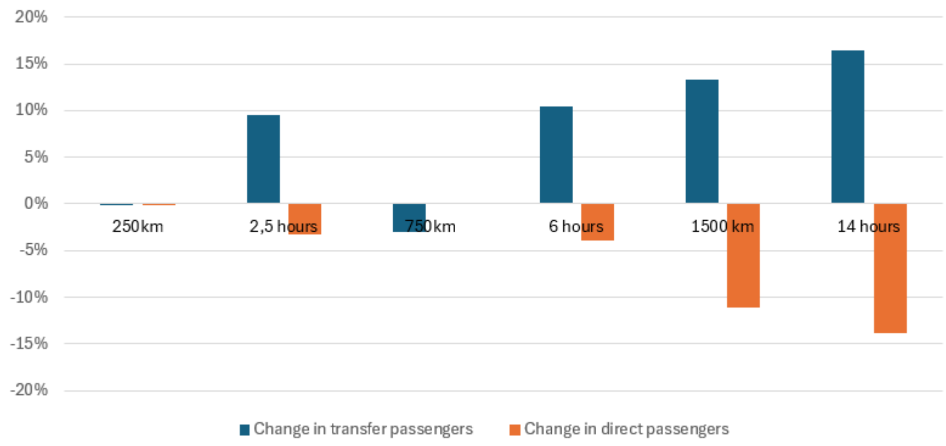



**Figure 6.2:** The difference between people choosing to travel directly or via transfer to their final destination, compared to the no-ban alternative.

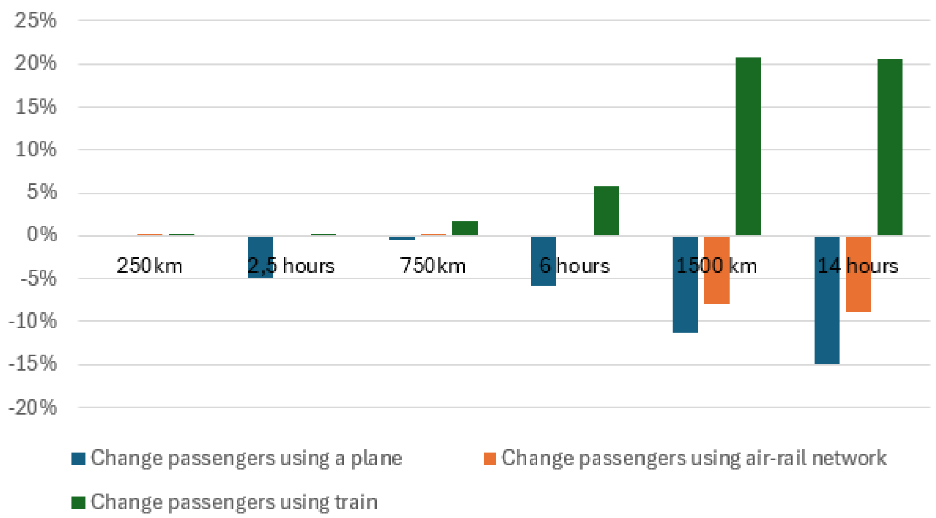



**Figure 6.3:** The difference in transport choices by alternative compared to the scenario where no ban applies.

In the 250 km distance-based ban, only minor behavioral changes are observed. A small group of passengers switches from air travel to rail, and there is a slight decrease in transfer passengers and direct passengers. In this scenario, many passengers have likely already switched to the HSR or Air-Rail alternative. This means that the 250 km ban shows little difference from the base scenario, except that the remaining passengers on really short flights are now forced to travel by HSR or take a direct flight. Also there is a small increase in Air-Rail passengers.

Under the 2.5-hour time-based ban, a clearer shift is visible. The number of passengers using high-speed rail (HSR) slightly increases, direct flights decrease, and transfer flights become more common. The number of Air-Rail passengers is slightly decreasing. Importantly, the use of planes decreases by 5% compared to the base scenario. This indicates that the 2.5-hour ban results in a small decrease in plane passengers and an increase in HSR use. However, only the direct use of HSR is growing, not the number of passengers using the Air-Rail network. It implies that passengers are not choosing the Air-Rail option but rather travelling around the ban. This is notable because the use of the Air-Rail network is declining, while the number of transfer passengers is rapidly increasing. The decline in Air-Rail use may be due to the existing fully functional HSR network, leading many passengers with the option of Air-Rail to choose this route already in the base scenario. When the ban has eliminated some routes in this scenario, is it logical that some passengers disappear.

Comparing the 250 km and 2.5-hour bans, it is evident that the 2.5-hour ban had a larger impact on mode choices than the 250 km ban. This effect is also observable when comparing the 750 km and 6-hour bans. In this case, the distance-based ban does not influence passenger choices, while the time-based ban has a larger impact on passenger mode choices.

Overall, the direction of the effects of all four scenarios is the same regarding mode choice. In all scenarios, the use of aircraft decreases while the use of HSR increases. Only the Air-Rail alternative shows differences; notably, the distance-based ban increases Air-Rail use, whereas the time-based ban decreases it. This may be because re-routing is more complicated under the distance-based ban, as there are fewer routes available. Consequently, it is likely faster for a passenger to take the HSR after a flight than to fly around the ban. So it seems that the flying distance of the detour influences passengers' choice behaviour. However, the average distance passengers have to detour was not determined in this study.

With the 750 km ban, passenger behaviour shifts different than the time-based alternatives. There is a reduction in transfers within Europe and increased HSR usage. Also the usage of Air-Rail is increasing slightly, but this is very limited. The 6-hour ban shows further growth in HSR usage, as seen in the 2.5-hour scenario. Additionally, the number of transfer passengers is increasing, with a small reduction in direct passengers. This indicates that some passengers are attempting to fly around the ban. This is likely easier in the 6-hour scenario than in the 750 km scenario because more flight paths remain available in the 6-hour scenario. In the 750 km scenario, there was a decrease in transfer passengers, indicating that it is more challenging to travel around the ban in that scenario.

The results of the 1500 km and 14-hour bans look very similar. Both show a decrease in direct passengers and an increase in transfer passengers. However, the time-based ban has a larger impact on passenger choices than the distance-based ban. This differs when examining mode choices, as the number of HSR passengers grows slightly more under the distance-based ban than under the time-based ban. Notably, the use of the Air-Rail network in both types of scenarios decreases by more than 5%, indicating that a ban on short-haul flights will reduce the use of the Air-Rail network, while passenger choices seem to be shifting toward the direct HSR alternative.

## 6.3. The impact of the ban on CO2 emissions

To say something about the CO2 emissions of aviation after the introduction of a ban on short-haul flights, the average difference compared to the base scenario was considered. Using these results, an attempt is made to illustrate the impact of various scenarios of the ban on CO2 emissions in the aviation market. Figure 6.4 shows the different result about the CO2 emissions.

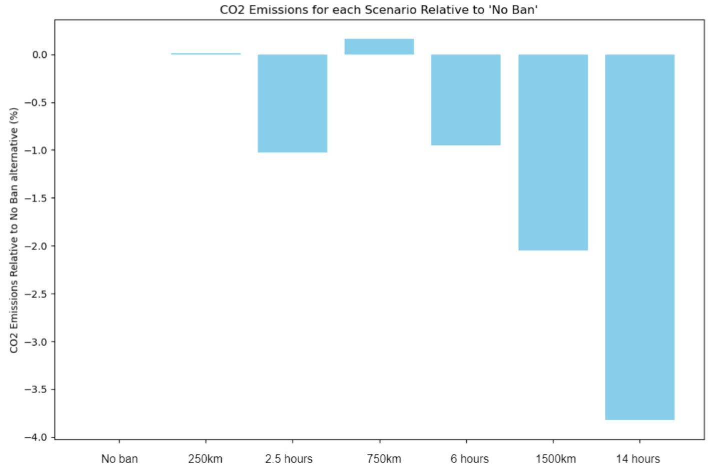



**Figure 6.4:** The difference in CO2 emissions based on the No Ban scenario, where no ban on short-haul flights is in place.

The first thing to notice is that when the ban is set at 250 km or 750 km, CO2 emissions do not decrease; in fact, they slightly increase compared to the base scenario. Examining passenger mode choices reveals that these two scenarios have little impact on mode selection. However, when comparing mode choices with CO2 emissions, it is evident that the group flying now takes larger detours, resulting in increased CO2 emissions. This is likely due to the design of the ban, as it does not consider possible HSR routes. As a result, a passenger may need to travel around the ban, likely increasing the flight distance they must cover. This suggests that a passenger's detour distance impacts CO2 emissions.

In the time-based scenarios, particularly the 2.5-hour and 6-hour bans, there is a slight decrease in aviation CO2 emissions. Notably, the 2.5-hour ban results in a greater reduction in CO2 than the 6-hour ban. In both time-based scenarios, the number of HSR passengers is increasing, suggesting that removing plane options on competitive HSR routes leads to a reduction in CO2 emissions. It is important to note that in the base scenario, a fully functional HSR network is used, so the train competes with planes on more routes than in reality.

Considering the two extreme alternatives, the 1500 km and 14-hour bans effectively eliminate short-haul flights. The reduction in CO2 emissions from aviation due to these bans is modest compared to the base scenario, yielding a maximum reduction of only 4% for the 14-hour ban, while the 1500 km scenario shows a reduction of 2%. This indicates that even with a fully functional HSR infrastructure, a complete ban has a limited impact on CO2 emissions. However, it may be that much of the CO2 emissions have already been reduced by the base case; as a result, the emission reductions due to the ban are relatively low. This indicates that, once a fully functioning HSR network is available in Europe, a ban on short-haul flights has a minimal effect on further reduction of CO2 emissions from aviation.

Revisiting the structure of both types of bans in the complete ban scenario, it can be observed that the time-based ban restricts fewer routes. Consequently, there are more flight options available to passengers, resulting in a shorter distance for rerouting. This is in contrast to the distance-based ban, which has a higher average detour distance and fewer transfer passengers. Since the time-based ban leads to a greater reduction in CO2 emissions, it is evident that a balance must be struck between the extent of the ban and the average detour distance for passengers. This variable is likely to have a more significant impact on CO2 reduction than the number of transfer passengers. The variable of average detour distance was not examined in this study.

## 6.4. The impact of the ban on different hubs

Besides the overall picture of CO2, this study also tried to map the impact of the ban on different airports in Europe, with a focus on hubs. To assess this impact, four different figures were designed. Each figure shows different hubs. For each hub, the total number of passengers leaving the hub by plane was considered. This number was then compared to the base. The numbers can be found in Appendix H. Figure 6.5, 6.6, 6.7, 6.8, 6.9 and 6.10 illustrate how each scenario will impact different hubs based on the numbers that can be found in Appendix H. The figures represents different scenario's were each scenario is compared to the base scenario.

Ultimately, the different scenario's are compared to provide each hub with an average effect, this result is shown in Figure 6.11. First, the overall effect of each scenario on different hubs will be addressed; then the overall impact of the different scenario's on various hubs will be examined.

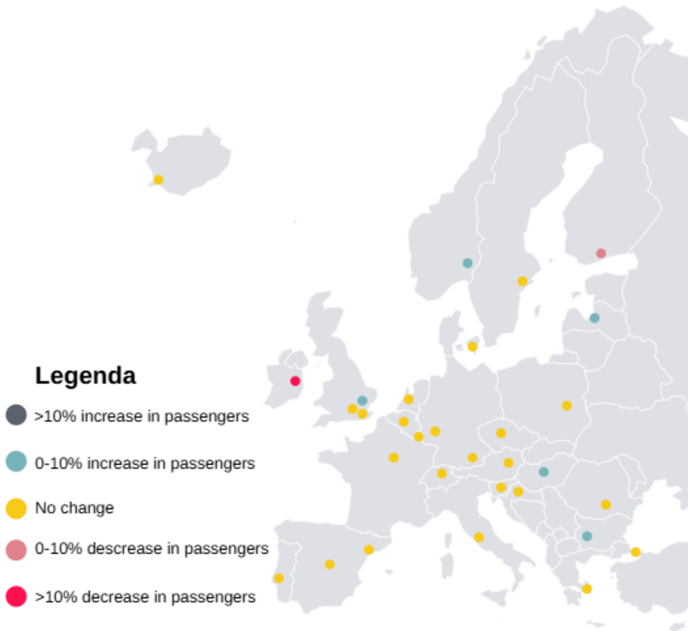



**Figure 6.5:** The impact of a ban of 250 km on passengers departing from airports around Europe

The results on the hubs of a 250-km ban are shown in Figure 6.5. This ban has little impact on the various hubs. As had been seen in the passenger choices were in this scenario no big changes in passenger behaviour were noted. This is probably because there is already a full functioning HSR infrastructure that assigns passengers towards the HSR. So, it appears that in the base scenario at distances of 250 km, a large proportion of passengers have switched to trains, suggesting that this particular ban has little impact on passenger travel behaviour. Consequently, there are minimal changes compared to the base case for the different hubs.

Notably, Dublin Airport loses a significant number of passengers, probably because it is close towards the UK, and Dublin airport is the only hub in Great Britten that is affected by the ban. So maybe it is better for passengers to chose routes using airports in the UK, what could explain the lost in passengers by Dublin.

It can also be observed that a few smaller airports, such as Oslo airport, Riga airport, London Stansted, and Sofia airport, will see a slight increase in passenger numbers. This can be the case because small hubs have a low proportion of passengers in the input data, so a small increase will have a larger impact on these airports. Furthermore, these locations are noteworthy as the small airports experiencing this increase are located more towards the edges of Europe.

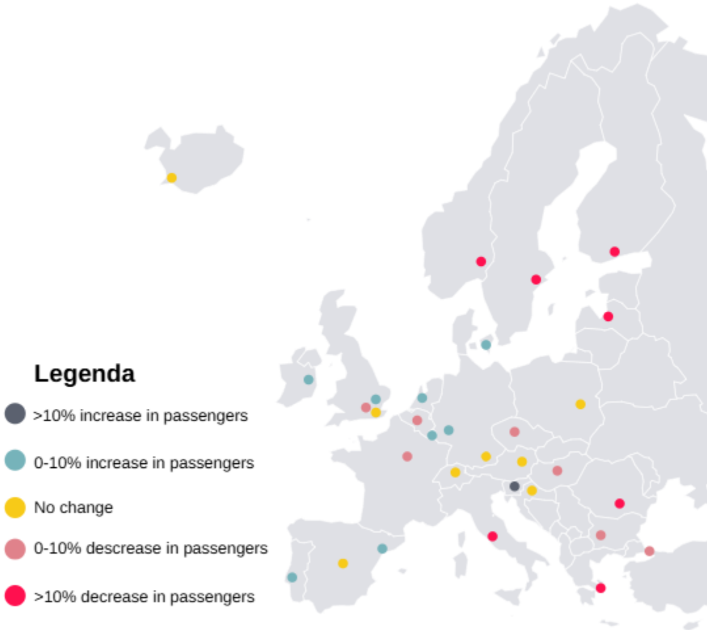



**Figure 6.6:** The impact of a ban of 2.5 hours on passengers departing from airports around Europe

The first thing that needs to be addressed from Figure 6.6, is that there are much more changes in passenger choices in this scenario, than in the scenario of 250km. This is remarkable because the scenario's should have more or less the same impact on passenger choices.

Remarkably, the larger hubs in Western Europe experience slight growth in passenger numbers in this scenario compared to the baseline. In contrast, smaller hubs in Eastern Europe and other EU member states show a small decline in passenger numbers. This may be due to larger hubs having more routes available; when shorter routes are lost, they can compensate with other options. In contrast, smaller airports have a more limited route supply, so the loss of routes will more quickly impact their passenger numbers.

A clear winner is Ljubljana Airport, which gains a substantial group of passengers. This effect is likely pronounced because Ljubljana Airport is the smallest hub in the study, so even a small change can have a significant impact. But still is this a very striking result. It may be that routes through this hub may now be the only logical choice for passengers, as other hubs in the area are experiencing a loss of passengers in some cases. This may mean that these hubs lose routes that Ljubljana can operate, leading to Ljubljana taking over some of these passengers.

A few losers also emerge in this scenario. For instance, airports in northern Europe, eastern Europe, as well as Rome-Fiumicino Airport and Athens Airport, experience passenger losses. A possible explanation is that, due to their locations, they are losing passengers. It is interesting to notice that hubs in the western side of Europe, are gaining passengers while the eastern side has a lot of hubs that are losing passengers. It is also noteworthy that London Heathrow loses a small share of its passengers in this scenario.

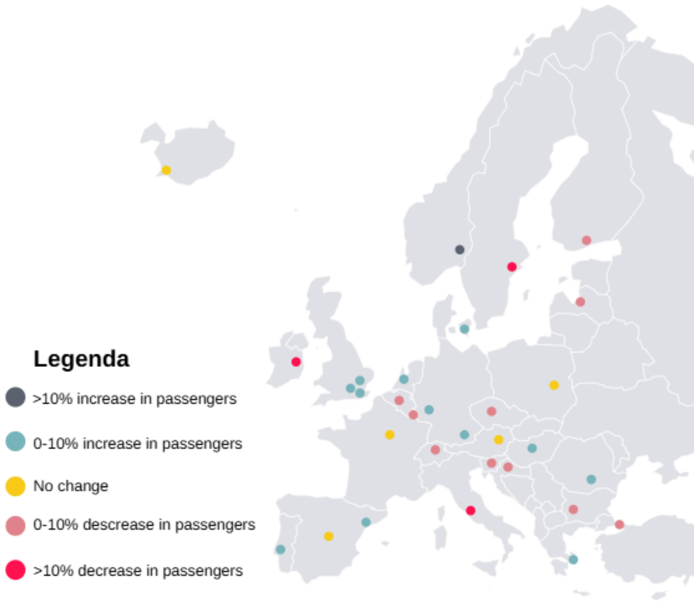



**Figure 6.7:** The impact of a ban of 750 km on passengers departing from airports around Europe

Figure 6.7 shows the effect of a 750 km ban on various hubs. The results show that hubs that are close to each other, that one of the hubs often experience an increase in passengers, particularly the larger ones. For example, Schiphol Airport has seen growth in passenger numbers, while Brussels Airport and Luxembourg Airport have experienced a decline. This suggests that larger hubs in a region are less impacted by the ban, likely because they can offset the loss of routes with other routes available at these airports.

Additionally, some hubs located towards the edges of Europe are experiencing growth. For instance, Oslo Airport's passenger numbers are increasing sharply, whereas they were previously declining; this suggests that passengers using Oslo may still be able to fly around the ban, which accounts for the increase. It is also noteworthy that all airports not located in EU member states are experiencing growth. With hubs growing in passenger numbers located more on the outskirts of Europe or in non-EU member states, this indicates that despite a larger ban, passengers are still attempting to circumvent it by using more remote hubs.

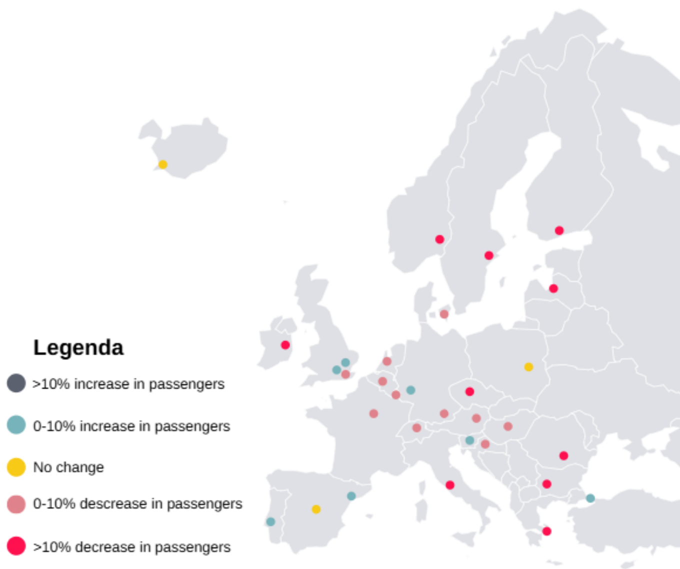



**Figure 6.8:** The impact of a ban of 6 hours on passengers departing from airports around Europe

Figure 6.8 shows the impact of a 6-hour ban. In this scenario, it seems that the hubs are divided into groups that lay more or less in the same region. This means that one of several hubs in close proximity experiences growth while the others shrink. This indicates that a nearby hub can still accommodate a share of passengers, while the others are negatively affected by the ban. Thus, growth depends on the location of the hub. It is also noticeable that primarily the larger hubs with more connections experience an increase, while smaller hubs decline.

It is clear that location plays a major role; for instance, hubs in northern Europe all suffer a loss of passengers. Additionally, Roma-Fiumicino airport is notably affected. Interestingly, airports in Spain and Portugal see an increase in passengers. This may be due to their convenient locations in relation to viable route options, allowing these airports to retain many routes. Consequently, more passengers are choosing these airports.

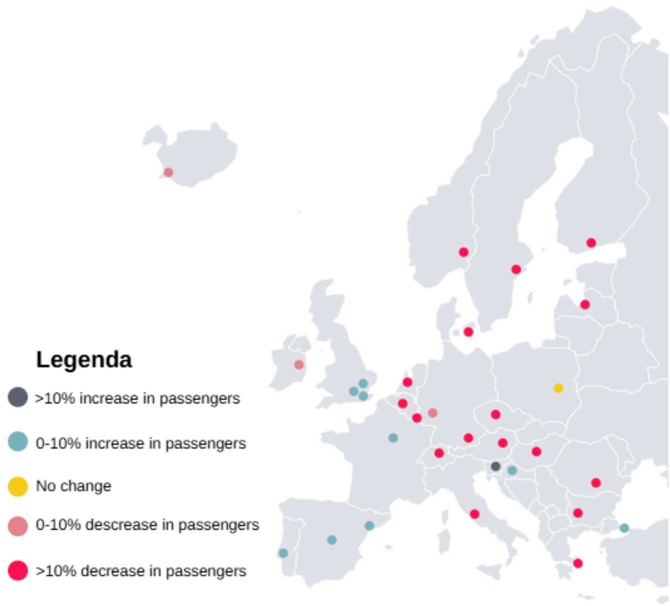



**Figure 6.9:** The impact of a ban of 1500 km on passengers departing from airports around Europe

Figure 6.9 presents the 1,500-km ban. It reveals that nearly all hubs within the EU member states experience a decline in passenger numbers. Strikingly, however, airports in Spain and Portugal see an increase in passengers, and Charles de Gaulle in Paris also sees a growth. This indicates that the location of an airport influences the impact of the ban. Paris is particularly notable as it is more centrally located than airports in Spain and Portugal. It is therefore surprising that this airport shows an increase.

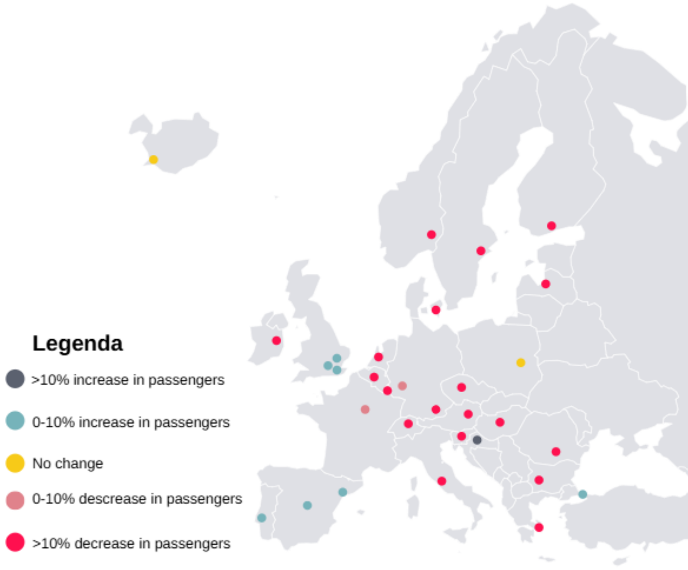



**Figure 6.10:** The impact of a ban of 14 hours on passengers departing from airports around Europe

Figure 6.10 illustrates the 14-hour ban, which exhibits the same effect as Figure 6.9. A significant difference is that, under this ban, Charles de Gaulle Airport (Paris) also experiences a loss of passengers, unlike the 1,500 km ban. Consequently, with this ban, Paris is no longer a viable transfer location.

Now each scenario is explained individuel, it is time to combine them in one map, to look at how the hubs are overall impacted by the ban. This overview can be seen in Figure 6.11. Under the figure the text will explain a few hubs and how they are effected.

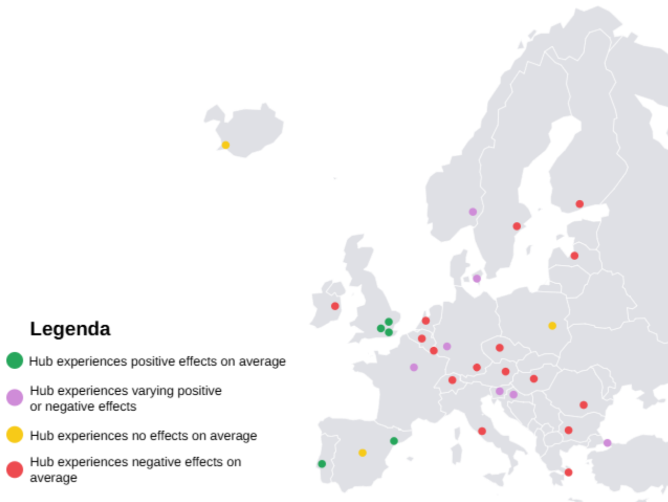



**Figure 6.11:** The average effect of the ban on different hubs around Europe.

Looking at the size of the airports, it appears that smaller airports (Brussel, Sofia, Prague, Baudapest, Dublin, Riga, Kopenhagen and Wenen) in particular are hit hard by the ban on short-haul flights. For instance, in Prague, a 250 km ban seems to have little impact on passenger numbers. However, this changes dramatically with other alternatives. The number of passengers flying over Prague can drop by as much as 50% in extreme cases. Similarly, at other small airports like Riga, a 250 km ban results in a slight increase in passengers, but this quickly turns negative in other scenarios. Notably, Riga has an HSR station. The airport was anticipated to attract more passengers with a time-based ban, but the results don't show this effect.

At larger airports like Schiphol, Frankfurt airport and Munich airport, a different picture emerges. Notably, with the 250 km and 2.5-hour ban for both airports, there is an increase in passenger numbers. This may be due to their excellent global connections, allowing passengers who transfer at Schiphol or Munich to bypass the ban. However, with the 6-hour ban, even these major hubs experience a decline in passenger numbers, and this effect intensifies in extreme scenarios.

Looking at the various airports, it is noticeable that most airports are losing passengers, but, there are exceptions. For instance, Barcelona Airport is seeing an increase in passengers despite the bans. This can be attributed to its location in Spain, on the edge of Europe, which results in fewer banned routes. As a result, passengers have more options, making Barcelona an appealing transfer airport. A similar effect is observed at Madrid airport. This effect can also be seen at Zagreb airport, but it only occurs when extreme bans are introduced.
Airports such as Finavia Airport, Stockholm-Arlanda and Rome Fiumicino will lose many travellers by introducing a ban on short-haul flights. These three airports are the biggest losers in such a ban. Probably because they lose more routes due to the ban. Because they are laying more central in Europe.

When looking at Ljubljana Airport, one striking effect stands out. This airport is located centrally in Europe, it is the smallest hub in this study. Notably, under various ban scenarios, the airport sees a growth in passenger numbers, with a decline only observed at the 750 km and 14-hour bans. At the 250 km ban, changes are minimal. This may be because, in the base scenario, a small proportion of passengers use this airport due to its limited connections. Consequently, the introduction of a new route can significantly impact passenger numbers. It may be coincidental that the removal of specific routes results in an increase in passengers at Ljubljana Airport, but it could also be because of the routes Ljublana offers to passengers which makes it more interesting to use this airport.

An interesting airport is Reykjavik-Keflavik, as it is hardly affected by the ban. This may be because there are few banned flights at the airport and transfers from other routes do not take place, resulting in an unchanged number of passengers. Moreover, the airport is not strategically located enough to attract other passengers. This may be due to the fact that transfers take longer than direct flights, and Reykjavik's location is halfway across the Atlantic Ocean. This crossing is offered direct by many airlines. Therefore, it makes sense that hardly any passengers would leave or gain when a ban is introduced.

Chapter 2 discussed several countries within and outside the European Union. This chapter highlighted the expectation that airports in England and Turkey would benefit significantly from the ban on short-haul flights, as they are not subject to EU regulations. Airports within the EU generally face passenger losses, while London Stansted shows growth in passenger numbers. The results suggests the potential for these airports to accommodate some of the passengers if in the EU a ban on short-haul flights is implemented. At London Heathrow and Istanbul Airport, a increase occurs when a large ban is implemented in Europe. Interestingly, these airports experience a slight decline in passengers during a small ban. For London Heathrow and Gatwick, this may be due to London Stansted, which attracts many passengers and thus impacts Heathrow and Gatwick. For Istanbul, the decline is harder to explain. One possibility is that EU airports provide sufficient alternatives for passengers during a ban, or that travellers prefer direct flights, as transfers to Istanbul are maybe less appealing.

Compared to the base scenario, it is evident that implementing a ban leads to a loss of passengers at several hubs within EU countries. On its own, this is not an issue, as the aim of the policy is to encourage more passengers to choose HSR. What is striking is that with any kind of ban, the EU can be divided into regions where one hub experiences an increase in passenger numbers while other hubs in the area lose passengers. This suggests that the location of a hub plays a significant role in the impact of the ban. If a hub's location allows it to maintain more flight routes, it tends to attract more passengers. The study did not examine how many routes a hub retains after the introduction of a ban, but it is noteworthy that hubs that have high connectivity in the base scenario in particular, experience an increase in some scenarios.

# 7 Conclusion

This chapter will discuss the conclusions drawn from this research. It will first address the various sub-questions, after which the main question will be answered based on these sub-questions. A discussion will then follow on the different conclusions and previous literature, followed with a discussion about the limitations of the model. Followed by suggestions for possible future research, and the report will conclude with a brief recommendation for the European Union.

## 7.1. Conclussion of the research questions

Several research questions were drawn up at the beginning of this study. After presenting the results, it is now time to discuss these questions and draw conclusions. This will be done by first answering the various sub-questions. These answers will then be used to answer the main question.

Before addressing the different conclusions, there are a few assumptions in the results that are important to mention. The first significant assumption is that the various scenarios have been compared to a baseline scenario, which assumes that Europe has an optimal HSR network. This implies that the CO2 changes resulting from the different scenarios have not been compared with reality but with aviation emissions in the baseline case. Additionally, this study has utilised self-developed demand based on 2019 and 2023 flight data. This means that the findings will not fully predict the future but will provide insights into what might occur if Europe has an optimal HSR network and the EU chooses to implement a ban on short-haul flights.

### 7.1.1. Conclusions of the different sub-research questions

**1. How can a ban on short-haul flights be designed, and what indicators could affect its impact?**

This study outlines two ways to implement a ban on short-haul flights. First, a distance-based ban can be established, assessing flight distance to determine prohibition. The second method is a time-based ban, which considers whether the HSR can connect two cities within a specific timeframe; if it can, flights between those cities are banned. In the results can be seen that a ban based on time results in a lower CO2 emission by aviation, than a ban based on distance. The 14 hours alternative results in the lowest CO2 emissions by planes in Europe, compared to the base scenario.

The main difference between these two types of bans is that the time-based ban considers potential alternatives. This is a significant disadvantage of the distance-based ban, as it may reduce the accessibility of cities in Europe. The time-based ban accounts for possible HSR alternatives, maintaining the accessibility of European cities. However, the disadvantage of the time-based ban lies in its challenging implementation. When implementing this ban, the speed of travel between European cities must first be assessed. Then, it must be determined which airports will be connected to cities to identify which short-haul flights will be banned. While implementing the distance-based ban is straightforward, it results in reduced accessibility for European cities. In contrast, although the time-based ban preserves the accessibility of European cities, it is considerably more complex to enact.

The results show that implementing both types of ban leads to more passengers choosing an HSR alternative. However, it is evident that transfer passengers influence the effectiveness of the ban. This is particularly clear with the 250-km ban, where hardly any changes are observed in passengers' transport choices. The use of direct flights and the number of transfer passengers both decrease. In this scenario, compared to the base case, CO2 emissions increase. Since direct flights produce fewer emissions than multiple flights, and the share of passengers flying direct decreases, the number of transfer passengers also declines. This indicates that the rise in CO2 emissions is not due to direct passengers; the only alternative is that transfer passengers travel longer distances on average. Based on the results, the primary indicator of the ban's impact appears not to be the number of transfer passengers, but rather the average extra distance a transfer passenger must travel due to the ban. The effectiveness of the ban also relies on other factors, but from this study's findings, the average flight distance of a transfer passenger seems to be the most significant indicator. This study did not examine how this value varies between a ban based on time and distance; future research may find it worthwhile to explore this variable and its impact on CO2 emissions.

**2. How can a base scenario be developed to research the effects of the ban on short-haul flights?**

A base scenario was developed to address limitations in the input data and the inherent inaccuracies of modelling real-world systems. Since the original dataset only included airport-based information, the origins of passengers were unknown, making the creation of a base scenario necessary. To account for unrepresented transfer passengers, a frequency-based reallocation method was introduced. While this method aligns with expected outcomes, it cannot fully replicate reality due to the simplified assumptions in the model. Nevertheless, for analysing passenger choice behaviour, this limitation is deemed acceptable. However, the method is not suitable for producing precise passenger forecasts. To enhance the method's effectiveness, airlines could be more actively involved. Currently, it is considered solely from the passengers' perspective, while the airlines at airports decide which routes they serve. Examining the hub-and-spoke network, the choices made by these airlines and their alliances can also shed light on the behaviour of transfer passengers. This has not yet been addressed in this study, as the research has focused on establishing the method's foundation.

The base scenario revealed that a significant share of passengers would opt for HSR, despite the input data being derived from air travel. This suggests that with a fully functional HSR network in Europe, a large group of passengers would likely choose HSR over air travel. This research did not examine the effect of this shift on CO2 emissions from aviation, but it can be inferred that there will be some impact. Therefore, it can be concluded that a well-functioning HSR network can attract more passengers to an integrated Air-Rail network and the direct HSR network. However, the real-world implications of this shift require further research on CO2 emission differences to fully understand how a well-functioning HSR network will affect the current situation.

**3. How will passenger mode choice affect CO2 emissions in the aviation sector for each type of ban on short-haul flights?**

The results show that the time-based ban strongly influences passengers' mode choices. This effect is less pronounced for the distance-based ban. However, in both types of bans, the share of passengers opting for the HSR continues to rise. This was observed while comparing the different scenarios with a base scenario featuring a well-functioning HSR network. Therefore, the ban on short-haul flights can still lead to an increase in the share of passengers choosing the HSR, after a HSR network is fully optimized.

Notably, the share of transfer passengers increases in most scenarios; this does not occur in the 250 km and 750 km scenarios. However, because fewer flight routes are prohibited under the time-based ban, this result suggests that passengers will opt to travel around the ban if possible. There appears to be a connection between the routes that are removed and passengers' choice to take multiple flights. This indicates that at a certain point, direct flights in Europe are so limited that passengers have no choice but to use transfer flights, or there are to much flights available so they chose to use multiple flights. It may be interesting to research the availability of flights and how this influences passenger choices, to gain a better understanding of why a small distance-based ban leads to a decrease in transfer passengers, whereas a time-based ban of the same kind results in an increase in transfer passengers.

It is noteworthy that in the time-based ban, the share of transfer passengers increases while CO2 emissions decrease. This indicates that a larger increase in transfer passengers does not necessarily lead to a significant rise in CO2 emissions; rather, other factors influencing transfer passengers affect CO2 emissions. For example as mentioned before the average detour distance of a transfer passenger.

Examining the results, the reduction in CO2 emissions is, at best, around 4%. However, since there was no comparison with the current HSR network, it is difficult to determine whether this impact is significant or negligible. What can be concluded is that if there is a well-functioning HSR network in Europe, a ban on short-haul flights can still lead to a modest reduction in CO2 emissions. However, this only applies to a ban based on time; for a ban based on distance, it is only feasible if a ban of 1500 km is implemented.

**4. Does the ban on short-haul flights promote the use of the Air-Rail network?**

The results indicate that with a fully functional HSR infrastructure, a significant proportion of passengers opt for the Air-Rail option. When HSR is operating optimally, a ban does little to encourage the use of the Air-Rail network and may even hinder it. Only with a ban of 250 km and 750 km is there an increase in Air-Rail passengers, likely because the other options are very limited. This may occur if a passenger wants to travel a short distance and then use the train, as this route disappears due to the ban. It remains easy for passengers travelling longer distances to reach other hubs and take a second flight from there. This conclusion is supported by the growth in departing passenger numbers at different hubs. It can be seen that hubs located on the edge of Europe experience slight growth due to the ban. This suggests that a passenger travelling from, for example, South America to Brussels and taking multiple flights is more likely to choose to fly via Barcelona to bypass the ban rather than opting for the Air-Rail network. Additionally, it could be that passengers wishing to use the Air-Rail network have already been directed to these alternatives by the well-functioning HSR network. The results therefore show that a ban on short-haul flights, with an optimal HSR network, does not further promote the use of the Air-Rail network.

**5: How will a ban on short-haul flights change the competitive position of hubs across Europe?**

In the expectations of this study, it was assumed that the hubs in Europe would lose passengers as a result of the ban. This study did not investigate this in detail, but it is possible that by optimising the HSR infrastructure, the hubs are already experiencing a loss of passengers. The results were therefore compared from this starting point. Examining the results, it can be seen that various hubs are still feeling the effects of the disappearance of routes following the ban. The findings indicated that the impact of the ban depends on two key factors: the location and the size of the hub before the ban was introduced.

The results show that the most significant factor is the location of a hub. It is notable that in certain scenarios, hubs located at the edge of Europe experience growth. For example, Barcelona Airport shows growth despite the 750 km ban. This could be because the hub is situated on the edge of Europe. In contrast, Rome-Fiumicino loses departing passengers in this scenario. Being more centrally located, Rome-Fiumicino loses more routes due to the presence of airports to the west, north, and east of the hub from which routes are removed. In comparison, for Barcelona, the removal of routes mainly affects the north and east. To the west of Barcelona, there are routes for domestic flights, which were likely already served by the optimal HSR network. When the ban was introduced, these routes were already less significant for the airport. Because Barcelona Airport's location is more advantageous than that of Rome-Fiumicino, the number of routes removed is likely lower for Barcelona than for Rome. As a result, the connectivity of Barcelona Airport will be higher than that of Rome-Fiumicino, making it more attractive for transfer passengers. Consequently, the findings indicate that a hub will experience an increase in passengers.

The second factor is the size of the hubs, which plays an important role in their impact. If a hub could offer a large number of routes before the ban was introduced, it is likely that this remains the case even as routes are removed due to the ban. This is particularly evident in the 750 km scenario, where many routes have already been banned. However, it is still noticeable that major hubs in Europe experience passenger growth, while smaller hubs are already shrinking.

In conclusion, at the beginning of the study, it was indicated that an important characteristic of a hub is its connectivity. This study did not examine how many routes per airport were banned in each scenario, but the results imply that connectivity enhances the attractiveness of a hub within the hub-and-spoke network. Therefore, the results show that if a hub is favourably located, resulting in fewer routes being removed, or if a hub already had a large network and is therefore less affected by the ban, these hubs will experience a lesser impact from the effects of the ban, or even a growth due to the ban.

### 7.1.2. The response to the primary research question

The aim of this study was to investigate how passenger mode choices would influence the impact of a ban on short-haul flights, assuming that the European HSR network is fully developed and functioning effectively. Previous research primarily focused on short trips and individuals wishing to travel within the distance of the ban. Therefore, this study also examined whether transfer passengers influence the impact of the ban and how hubs in Europe are affected by it. Finally, it investigated how the ban affects CO2 emissions from aviation in Europe. All of this was based on the following research question.

**How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?**

The study compared the ban with a baseline scenario in which a fully functional HSR network was constructed. This baseline scenario produced interesting results. The input data consisted entirely of airline passengers. The results showed that by optimising the HSR route, some passengers were already willing to use HSR as a mode of transport instead of aircraft. The proportion of passengers using the Air-Rail network also increased. Therefore, the results indicate that by improving the HSR network, some passengers would choose not to use an aircraft. However, this does not mean that the proportion willing to choose the optimised HSR network would actually make that choice. The study based passenger choices solely on travel time with minimal consideration for comfort; travel costs were not included. Furthermore, the effect of this optimisation on CO2 emissions compared to reality was not examined. The only conclusion that this research can draw in this area is that by optimising the HSR network, there is a good chance that a proportion of passengers will be prepared to use the HSR instead of the plane.

The ban on short-haul flights has been developed in two different ways in this research: a ban based on time and a ban based on distance. The results show that only the time-based ban results in a reduction in CO2 across all scenarios. With the distance-based ban, this only occurs with a complete ban on short-haul flights. This indicates that when there is a well-functioning HSR network in Europe, a time-based ban can still lead to a reduction in CO2 emissions from aviation. However, it has not been investigated whether this is also the case if the current HSR network is applied in the research.

Previous research paid little attention to the effect of transfer passengers on the impact of the ban on CO2 emissions. This research shows that these transfer passengers do influence the impact of the ban, particularly evident in the 250 km scenario. In this scenario, there is little change in passengers' choice behaviour, yet CO2 emissions from aviation still increase. As HSR use increases and direct passengers decrease, the results show that the increase in CO2 must be due by transfer passengers.

Examining the differences in behavioural choices of passengers under a time-based ban versus a distance-based ban reveals that a time-based ban leads to a faster growth in transfer passengers, while this is not the case with a distance-based ban. The research demonstrates that transfer passengers influence the impact of the ban on CO2 emissions from aviation, but this does not depend on the number of passengers, rather on the average distance a transfer passenger must cover due to the ban.

For the Air-Rail network, this research shows that by optimising the HSR network, utilisation of this network increases significantly. The study cannot confirm whether this is due to HSR stations at airports, but it is likely that this plays a role. At the time the ban is implemented, there will be little increase in passengers on the Air-Rail network. It is more likely that there will be a decrease in Air-Rail use. This does not have to be detrimental; if passengers switch to HSR, it can still lead to a reduction in CO2 emissions.

The impact of the ban varies among different hubs and depends on specific scenarios. Notably, the impact depends on the location and size of the airport before the ban is implemented. These two factors influence the connectivity of a hub when a ban on short-haul flights is enacted; a hub with high connectivity after the implementation of the ban has a greater chance of experiencing an increase in passenger numbers. This research cannot say whether the hubs will disappear due to the ban, but it does indicate that the impact on some hubs could be significant.

In conclusion, this study shows that when Europe has a well-functioning HSR network, a time-based ban on short-haul flights can still lead to a small reduction in CO2. The impact of this ban is influenced by the route choices of transfer passengers and the distances they must detour. Air-Rail use will not significantly increase when the ban is implemented if a good HSR network is already in place, it is more likely to decrease. Additionally, the ban will have a considerable negative impact on passenger numbers in several smaller hubs within EU member states, but whether these hubs will also disappear remains uncertain. Thus, a ban on short-haul flights will affect the EU, but it is questionable whether this impact is desirable.

## 7.2. Discussion

Now that the conclusions have been drawn from this research, there will be a discussion of the findings. The discussion will first focus on the practical implications of the conclusions. Then, the conclusions will be compared to previous literature. The limitations of this research will also be briefly addressed. Based on the discussion and conclusion, potential areas for future research will be discussed.

### 7.2.1. Discussion

This study is the first to use this method to predict passengers' behavioral choices during a ban on short-haul flights. The method primarily focused on passengers' transfer times, excluding travel costs. The findings indicate that when a well-functioning high-speed rail (HSR) network exists in Europe, some passengers are willing to choose HSR. However, it remains uncertain whether this holds true when travel costs are factored in. In order to get a good picture of the effects of the ban on Europe in the presence of a well-functioning HSR network, it remains therefore still relevant to examine how travel costs influence passenger choices.

This study assumes that a well-functioning HSR network is being developed in Europe. Using a baseline scenario in which this network has been established, different scenarios have been compared. Previous research by Baumeister & Leung (2020) indicated that a study in Finland, where a ban was implemented, would result in a 95% reduction in CO2 emissions in the transport sector. In Baumeister & Leung (2020) study, the possible alternatives for passenger transport consisted of the existing national train network. When comparing this study with Baumeister & Leung (2020) findings, it can be argued that a ban on short-haul flights would reduce CO2 emissions in the aviation sector in Europe. However, this will be influenced by transfer passengers, which could result in an increase in CO2 emissions due to the ban. While Baumeister & Leung (2020) study suggests that a ban on short-haul flights could significantly affect CO2 emissions in the transport sector, this study indicates that, if the ban is implemented at a European level, transfer passengers may negatively affect CO2 emissions. As this study does not utilise the current HSR or train network, it remains unclear how the reduction in CO2 emissions would be. It may therefore be worthwhile to repeat this study using the existing HSR network in Europe.

The study shows that transfer passengers influence the effectiveness of the ban on short-haul flights. To determine which type or size of ban will positively impact Europe, the study revealed that this depends not on the number of transfer passengers but on the average distance they must detour. While the number of transfer passengers may still play a role, it is less significant than distance. This study identified a connection between these two variables and the overall CO2 reduction resulting from the ban. The results are considered logical and do not indicate to come from an error in the model. Therefore, it can be expected that the average detour distance of transfer passengers will also play a role in reality. It may still be worthwhile to explore the relationship between the average detour distance of transfer passengers and the number of transfer passengers in a potential follow-up study. This could help identify which type and size of the ban would lead to a reduction in CO2 emissions in Europe. The expectation is that if these two variables are balanced, a scenario can be found that maximises CO2 reduction if a ban on short-haul flights is implemented in Europe.

In Europe, the ban appears to redistribute passengers, particularly affecting smaller hubs. The study indicates that fewer passengers will travel from various European hubs, leading to decreased turnover at these hubs and raising concerns about the potential disappearance of some. It is clear that the ban will impact hubs, and future research should examine how this will affect different regions connectivity and economical.

### 7.2.2. The limitations of the model

The study had two major limitations that could have affected the results. The first was the lack of available data on passenger demand between different cities. To estimate how many passengers wanted to travel between cities, data from Eurostat (2025) was used, indicating the number of passengers who travelled between two airports in 2023. The issue with this data is that it does not account for transfer passengers, leading to double counting. To allocate these transfer passengers to their original departure and destination, the Frequency-based reallocation method was employed. This method was specifically developed for this study and has not been used before in existing literature. However, it only considers departing passengers and potential illogical transfers, neglecting other possible factors. For instance, passengers may choose specific airlines or alliances. If an airline operates a hub-and-spoke strategy, the likelihood that a passenger will fly to the airline's home hub is significantly higher than on the largest route departing from a specific airport. Therefore, it would be beneficial for future research to explore whether these airlines or alliances can influence the frequency-based reallocation method to better explain passenger travel behaviour.

Another major limitation of this study was the computing power used to calculate the algorithm. To minimise computing time, a maximum number of iterations was set for the k-shortest path algorithm. Consequently, the algorithm could not calculate all possible route options. As a result, some more complicated routes for passengers may not have been identified, leading to an overestimation of the number of passengers using certain routes. When interpreting the data, it is important to recognise that this model did not predict a future scenario that corresponds 100 per cent to reality.

### 7.2.3. Future research

Based on the discussion and conclusion, several suggestions have been identified that may be worth investigating in future research. Below is a list of the various suggestions for future research arising from this study.

- What is the average detour distance for transfer passengers when a ban on short-haul flights is implemented in Europe?
- How will the ban on short-haul flights impact CO2 emissions in aviation, assuming the current HSR infrastructure is used as an alternative?
- How will travel costs influence passenger choices when the HSR infrastructure is optimally developed?
- What are the economic consequences for hub regions when a ban on short-haul flights is implemented in Europe?
- How can airline routes be incorporated into the frequency-based reallocation method?

## 7.3. Recommendation for policy makers

This study is the first to investigate the effect of a ban on short-haul flights in Europe, considering transfer passengers and a fully operational HSR network. It aims to provide insights into the impact of this ban on various hubs in Europe and the CO2 emissions from aviation. The findings indicate that it is crucial to assess the effect of the ban on transfer passengers, as this group influences its impact on CO2 emissions.

According to the report, it is challenging to determine whether a ban should be implemented in Europe. Before any ban is enacted, further research is necessary to understand its economic effects on various hubs. Additionally, comparing the current HSR network in Europe with the potential impacts of the ban would be beneficial. The results suggest that investing in a good HSR network could lead to a significant reduction in CO2 emissions from the transport sector, although this conclusion cannot be fully supported by the study's results.

Therefore, the recommendation to the European Union is to conduct further research on the ban's impact on hubs and CO2 emissions with the current European HSR network. The results of this study suggest that a ban on short-haul flights could lead to a reduction in aviation CO2 emissions. If a strong HSR network exists in Europe, it would be sensible for the EU to implement a ban based on travel time within Europe. The value of this ban should depend on its impact on the accessibility of regions and the economy in different areas.

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# A

# Scientific Paper

*The paper starts at the next page*

# The impact of a ban on short-haul flights on transfer passengers and CO2 emissions

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## Abstract

This study investigates the impact of a ban on short-haul flights in Europe on transfer passengers and CO2 emissions, focusing on both time-based and distance-based bans. Employing a route assignment analysis of a base scenario of Europe with an optimal High-Speed Rail (HSR) netwerk, compared with various scenario's of a ban. Results reveal that the impact of the ban on CO2 emissions is influenced by transfer passengers, primarily due to their average detour distance. The effects on different European hubs vary based on their geographical and operational characteristics. The findings suggest that a time-based ban could contribute to CO2 emission reductions, but more research is needed on the effects of the ban within the current HSR network in Europe. It is clear that the ban will impact hubs, and future research should examine how this will affect connectivity and economies in different regions.

***Keywords: Short-haul flight ban, Transfer passengers, High-speed rail (HSR), Air-Rail integration and Hub & Spoke network***

## I. Introduction

The environmental impact of aviation has become increasingly prominent in policy discussions, especially following the Paris Agreement. In response, the European Union (EU) wants to implement various initiatives aimed at reducing CO2 emissions in the transport sector, with a focus on reducing plane use. The aviation sector leaves a substantial ecological footprint due to the high frequency and energy demands of flights.

At this moment, air travel is the dominant mode of transport for long-distance journeys in Europe. This long-distance air travel can be divided into three types of flights: short-haul, medium-haul, and long-haul. Short-haul flights cover a maximum distance of 1,500 km and are mainly operated by low-cost and regional carriers. These flights are also an important type of flight in the hub-and-spoke network known as feeder flights. Short-haul flights are the most commonly used in Europe, accounting for 74.2% of all flights Dobravsky (2021). In Europe, these flights are responsible for 24.9% of total aviation CO2 emissions, as shown in Figure 1.

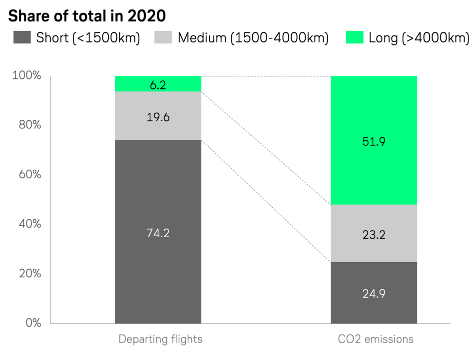


Figure 1: CO2 Short vs Medium vs Long distace flights (Dobravsky (2021))

To mitigate these environmental impacts, a proposed strategy is to integrate High Speed Rail (HSR) into the hub-and-spoke network (Givoni and Banister (2006)). This is because HSR produces less CO2 than planes (Prussi and Laura (2018)). Previous studies have demonstrated the feasibility and environmental benefits of HSR as a substitute for short-haul air travel-particularly for distances under 750 km, where rail is often faster or equally competitive in travel time (Adler et al. (2010)). The effectiveness of this integration is hindered by competition on the same routes between air and rail (Xia and Zhang (2017)). Additionally, many passengers still opt for short-haul flights within the hub-and-spoke network. To promote the use of HSR for shorter distances, the EU could implement a ban on short-haul flights. This would grant HSR a monopoly on certain routes, leading to an increase in passengers on HSR services. Since HSR emissions are lower than those of planes (Prussi and Laura (2018)), this should result in an overall reduction in CO2 emissions in the transport sector.

Despite these prospects, current literature presents mixed findings on the effectiveness of a short-haul flight ban. National case studie from Finland, show a reduction of 95% in Finland due to a ban on short-haul flights (Baumeister and Leung (2020)). A study by de Bortoli and Féraille (2024) shows also a improvement of the HSR average emissions, because more passengers choice the HSR.

There is little research in the current literature on how the ban on short-haul flights will affect the hub-and-spoke network. In particular, the impact of the ban on transfer passengers has not been considered. Transfer passengers originate from the hub-and-spoke network and use multiple flights to reach their final destination. Additionally, the effect of the ban on hubs in Europe has been understudied, as these hubs are central to the network and provide good accessibility to European cities, boosting the local economy (Volkhausen (2022)). It is important to examine how the ban will affect passenger flows through the various hubs. Furthermore, while a possible goal of the ban is to increase air-rail use in Europe, the effects of the ban on air-rail usage remain under explored.

By better understanding these passenger choices, it is possible to form a clearer picture of the ban's impact on aviation CO2 emissions. As the HSR network in Europe is currently not optimally developed and is considered in this study as the main alternative for short-haul flights, this study has chosen to optimise the HSR network in Europe to create a fully functioning HSR network in Europe. This research provides an opportunity to assess the effect of the ban on short-haul flights in Europe, provided that a well-functioning HSR network is in place, which also ensures an effective Air-Rail network. This research was conducted using the following research question and sub-questions.

**How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?**

**Sub-questions:**

- How can a ban on short-haul flights be designed, and what indicators could affect its impact?
- How can a base scenario be developed to research the effects of the ban on short-haul flights?
- How will passenger mode choice affect CO2 emissions in the aviation sector for each type of ban on short-haul flights?
- Does the ban on short-haul flights promote the use of the Air-Rail network?
- How will a ban on short-haul flights change the competitive position of hubs across Europe?

The rest of this paper will first discusses the indicators affecting the ban's effectiveness. Next, it outlines the methodology used in the study, followed by a discussion of various model parameters. This is followed by validation and verification of the model, leading to the results and conclusions. Finally, the paper discusses the findings and offers suggestions for future research.

## II. Ban on short-haul flights

This chapter will examine the implications of the ban on short-haul flights and its effects. It will begin with explaining the current state. After it will explain the design of the ban and how this will effect passenger choices. The chapter will conclude with the different expectations of the results.

### A. Origins of transfer passengers

In the aviation sector, passengers either travel directly or transfer through hubs, depending on airline strategies. Point-to-point carriers prioritise direct routes, often operating as low-cost carriers. In contrast, hub-and-spoke carriers use central hubs to connect regional feeders with long-haul flights, maximising aircraft occupancy and expanding service areas with fewer routes, as illustrated in Figure 2. For this reason, hubs have high connectivity with the world and provide economic benefits to the region around the hub(Volkhausen (2022)). Because transfer passengers must use multiple flights, the routes they travel often cover large flight distances and lead to high CO2 emissions. A key characteristic of such hubs is that they have high global connectivity and serve as a home base for a carrier that employs the hub-and-spoke strategy.

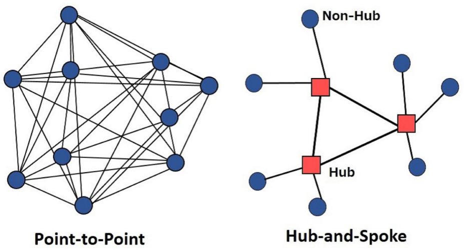


Figure 2: Point to point en hub and spoke design (Kuroki and Matsui (2024))

## B. The passenger choices in the current state

When a passenger wants to travel between two cities, they can choose from several transport options. To give an idea of the options a passenger has, there is made an example of a passenger that wants to travel between New York and Brussels. The various options for a passenger wishing to travel between New York and Brussels are shown in Figure 3

In this example, there are three possible routes a passenger can choose. The first option is a direct flight from New York to Brussels, which is a long-haul flight. The other two options involve transfers. In the first of these, the passenger takes a long-haul flight to Schiphol Airport and then transfers to a short-haul flight to reach the final destination. The last option is a long-haul flight to Heathrow in London, followed by a transfer to a short-haul flight to Brussels.

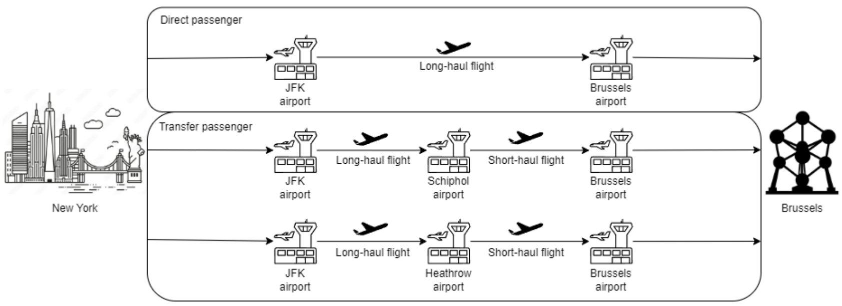


Figure 3: Three options for a passenger to travel between New York and Brussels

## C. Conceptual design of a ban on short-haul flights

A conceptual ban on short-haul flights can be approached in two main ways: a distance-based ban and a time-based ban. The distance-based ban prohibits flights between airports that fall below a specified minimum distance threshold. Its key advantage is simplicity, making it easy for policymakers and airlines to implement. However, this approach fails to account for geographical and infrastructural constraints, potentially limiting city-to-city connectivity when viable transport alternatives, such as rail or road, are unavailable. This could result in significant travel detours and increased emissions, undermining environmental objectives.

The second approach is a time-based ban that considers the availability and efficiency of high-speed rail (HSR) as an alternative. Flights are prohibited only if a train journey between two cities can be completed within a specified time limit. This method incorporates a component that links airports within a 50 km radius of a city, ensuring that policies are more context-sensitive and tailored to actual passenger options. This approach better addresses natural barriers and aims to maintain accessibility while reducing unnecessary short-haul flights.

Despite its benefits, the time-based ban presents implementation challenges. Its complexity requires detailed transport data and accurate assessment mechanisms, increasing the risk of administrative errors. Moreover, it may discourage investment in rail infrastructure, as cities might avoid improving HSR connections to maintain air route viability. Thus, while more equitable and efficient, the time-based ban demands careful governance to balance environmental goals with regional development and transport equity.

### D. Aspects affecting the effectiveness of the ban

The effectiveness of a ban on short-haul flights within Europe is influenced by several factors. Firstly, countries outside the EU pose a challenge, as the EU cannot enforce such a ban in non-member states.These non-EU members fall into three categories: EU candidate countries, Schengen-associated states, and non-EU members. While candidate countries may eventually adopt the ban through EU accession, Schengen-associated states would require individual negotiations but are also likely to implement the ban eventually. Therefore, the countries are considered as those that would implement the ban. Countries like the UK and Turkey, which are not members of the EU, are unlikely to comply, potentially creating opportunities for passengers to detour through hubs in the UK and Turkey. Figure 4 shows the different European countries and the category to which they belong.

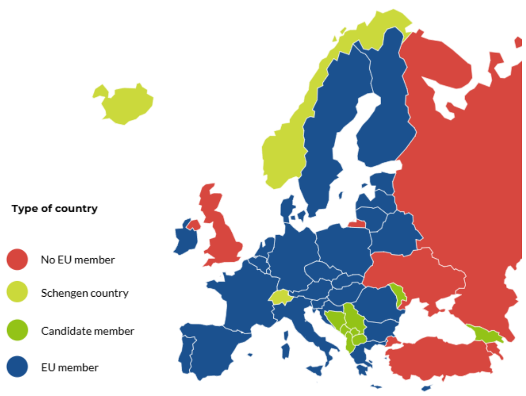


Figure 4: Members of the European Union and Non-EU members

Secondly, the availability and quality of HSR infrastructure play a role in providing viable alternatives to short-haul flights. HSR can effectively replace air travel on routes up to 750 km, but its current coverage in Europe is limited and uneven. High-speed lines require dedicated infrastructure capable of supporting speeds up to 300 km/h, yet many routes still operate on conventional tracks, limiting average speeds and accessibility. As such, a uniform ban without adequate rail alternatives could reduce connectivity for certain regions. For this reason, a fully constructed HSR network in Europe was selected for this study.

Finally, the integration of HSR into the existing air transport system through Air-Rail networks is essential. Seamless transfers between air and rail are facilitated by airport HSR stations, which reduce transit times and improve passenger convenience. When an airport has an HSR station, it is easier for a passenger to transfer from a flight to a train. However, not all major airports in Europe offer such connections. In their absence, passengers must rely on less efficient ground transport, such as taxis, to reach city rail stations, which may discourage the choice of the Air-Rail network. As noted in prior studies, effective Air-Rail integration is key to preserving hub-and-spoke connectivity while promoting sustainable transport modes. It also probably increases the likelihood that a passenger will choose an Air-Rail alternative. This study has therefore linked airports with a train station to the HSR network, despite the current absence of HSR train services at these stations.

### E. Expected effects of a ban on short-haul flights on a passenger

The implementation of a short-haul flight ban in Europe is expected to produce significant shifts in passenger behaviour and transport dynamics. Most notably, the ban will alter route choices for passengers. Figure 5 shows the impact of this ban on the previously mentioned example of a passenger wishing to travel between New York and Brussels. Due to the ban, this passenger can still take a direct flight between New York and Brussels; however, the transfer at Schiphol Airport is no longer available. Passengers can now choose to travel through London Heathrow, which is in the UK and not affected by the ban. This option is not beneficial because the distance the passenger travels will likely increase, leading to higher CO2 emissions. The alternative is to fly to Schiphol Airport and transfer to the HSR, which takes the passenger to Brussels. This means the passenger travels the same distance as before, but by choosing the HSR to reach Brussels, they will produce lower CO2 emissions than taking two flights.

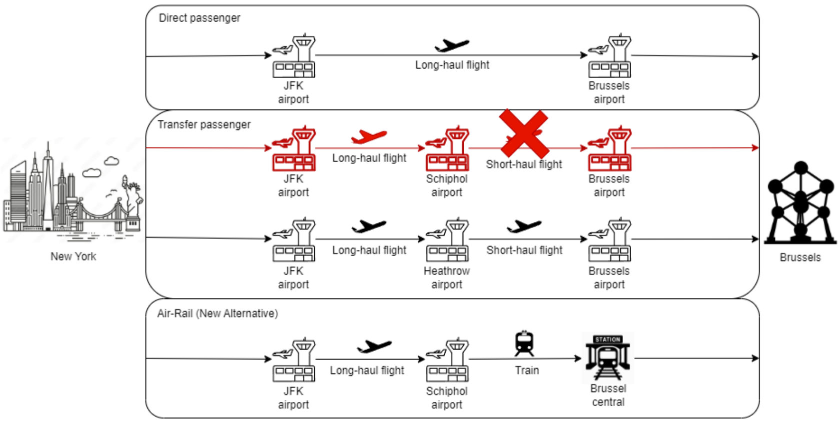


Figure 5: Route options for a passenger travelling between New York and Brussels when a ban on short-haul flights is in effect

A second example illustrates the impact on route choices for a passenger wishing to travel within the limits of the ban. The options for this passenger are shown in Figure 6, which depicts examples of route options between Barcelona and Brussels. As the figure shows, the passenger has a limited set of options available. Due to the ban, the direct flight and transfer flight through Schiphol are no longer viable. Additionally, the Air-Rail alternative is also unavailable for this passenger. Two options remain; the first is to take a flight to Heathrow Airport and transfer to a flight to Brussels. This will result in a high distance travelled by plane, leading to significant CO2 emissions. A cleaner alternative is for the passenger to take a direct train between Brussels and Barcelona, which will have lower CO2 emissions than the transfer option.

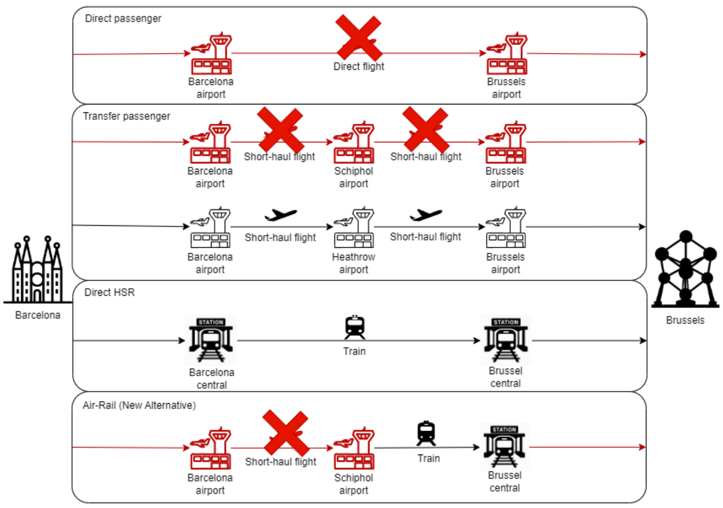


Figure 6: Route options for a passenger travelling between Barcelona and Brussels when a ban on short-haul flights is in effect

## F. The expected global effects of the ban on short-haul flights

The primary objective of the short-haul flight ban is reduce CO2 emissions, by promoting high-speed rail (HSR) usage. Based on Figure 5 and 6, HSR remains a viable option for both long-distance and some transfer journeys, suggesting a likely increase in HSR usage, particularly for direct connections. However, the impact on the Air-Rail network is less certain. While it may benefit long-distance travelers, it becomes unavailable for routes shorter than the ban threshold, potentially limiting its growth.

In aviation, the ban is expected to reduce direct intra-European flights, especially within the hub-and-spoke system where direct options are limited. This may lead to an increase in transfer passengers, including those rerouting through non-EU hubs unaffected by the ban, potentially increasing overall travel distances and associated CO2 emissions. So it is expected that the transfer passengers will influence the impact of the ban on CO2 emissions.

Thus, it can be suggested that the ban on short-haul flights could lead to a reduction in CO2 emissions, provided that the growth in HSR usage compensates for passengers flying around the ban. To assess the feasibility of this, The study has modelled passenger choices under the ban, estimating route selection, hub usage, and resulting aviation emissions to evaluate the policy's overall impact. Thereby, it is assumed that a fully functioning HSR network is in place in Europe.

# III. Method

This section discusses the method used in this study. To calculate passengers' mode choice, several steps were taken, each step consisting of different methods that contribute to the calculations. Since no data on passengers' current mode choices was available, a base scenario was developed first. This section explains how the base scenario was created and the adjustments needed to calculate different scenarios where a ban is implemented. It will also briefly discuss two key methods used in this study: the Frequency-based reallocation method and the random regret method.

## A. Global steps of the base scenario

To calculate the baseline scenario, several steps were taken, as shown in Figure 7. The figure illustrates two distinct calculation streams. The first flow involves calculating demand between cities, which is necessary because the input data comprises flight information between various hubs in Europe. Since the HSR starts and ends in cities, the data must be converted to trips between these locations. Additionally, the input data does not account for transfer passengers, so it is essential to predict the airports between which these passengers intend to travel. This flow is represented by blocks 2 and 3. The second flow involves developing a network, which consists of nodes and edges. Nodes are points where passengers wish to travel; in the model, a node can be either an airport or a city. The edges represent the routes passengers take, and each edge will eventually be assigned a number representing the number of passengers on that route. This flow consists of blocks 4 and 5.

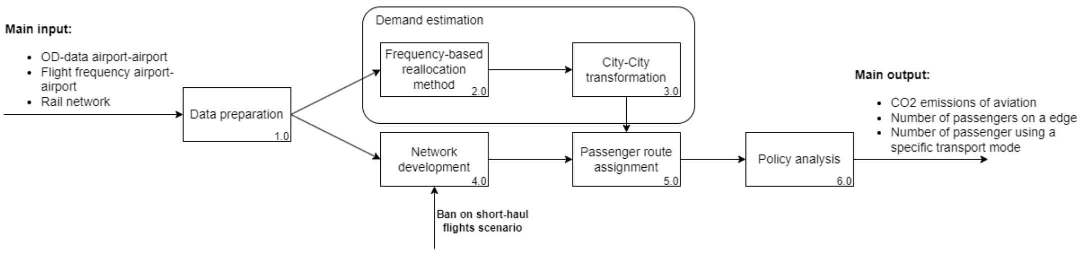


Figure 7: Different steps that the method of this study uses

The input data for this study is sourced from Eurostat (2025) and includes passenger numbers between different hubs for the year 2023. This does not include data for passengers from the UK, which is from 2019, potentially introducing slight bias for UK travelers. However, due to a lack of alternatives, this year was chosen. In addition to passenger numbers, the annual volume of flights between airports is also included, sourced from Eurostat (2025). The final input data consists of an HSR network optimized to connect all cities, with HSR stations added at airports. The HSR connections are based on the study by Grolle (2020) and current infrastructure plans published by Interrail-Eurail (2024).

The first step in developing the base scenario involves calculating various required data, as not all information is available. Therefore, some values are calculated from other accessible data. This includes calculating travel time between two cities by using the haversine method to determine distance and dividing that by the average speed of the respective transport mode. Each travel time also includes constants such as taxi time or transfer time. For HSR, this accounts for potential passenger transfers, while for aircraft, the average taxi time is added to the travel time. The constants used are listed in Table 1. In addition, a list was made of the different hubs that exist in Europe, for each hub there was looked at what the average transfer rates. This data can be found in Appendix A. A hub was selected for each EU country based on accessibility scores from ACI (2024). Some countries were assigned two hubs due to having two major airports.

| **What** | **Value** |
|---|---|
| Taxi Time | 15 min |
| Stop Time Train | 15 min |
| Average speed plane | 700 km/h |
| Average speed train | 220 km/h |
| Tolerance level | 50 km |
| Tolerance level non-EU | 100 km |

Table 1: Parameters

At the beginning of this chapter, it was indicated that the data used for this model is from Eurostat (2025) and consists solely of passengers traveling between two different airports. To adjust this data to a format suitable for passengers wishing to travel between two different cities, two steps are necessary. The first step, indicated in block 2.0, is required because the original data does not account for transfer passengers. As a result, passengers taking multiple flights are counted twice. To ensure that each passenger is counted only once in the model, the Frequency-based reallocation method was used. This newly developed method is specifically designed for this study because no existing method was found in the literature that could straightforwardly reallocate transfer passengers to their original origin and destination in an OD matrix.

When the data is adjusted for transfer passengers, it still doesn't indicate the origin or destination of a passenger. In block 3.0, an attempt will be made to assign different passengers to two cities between which they wish to travel. The city-to-city method is from previous research by Grolle (2020). The study by Grolle (2020), which uses the same data format, examines the allocation of passengers to cities. Since both studies are similar, this method can be applied to the current research. However, this study includes passengers traveling from outside Europe. As an adaptation to the original method, these passengers were allocated solely to air travel in the modal split. Additionally, the final step applied by Grolle (2020) was skipped, as including passengers from other transport modes is unnecessary for this study. The same parameters from his study are included in this study. The result of this step is an OD matrix in which passengers are assigned to their desired travel cities.

The initial step in developing the infrastructure begins with establishing the network (block 4.0). In this block, the rail and air networks will merge into a single connected system. This network will consist of various nodes and edges. The nodes represent airports and cities, while the edges represent possible rail or air routes. The value of these edges represents the travel time that is needed to complete a specific edge. Research from Flodén et al. (2017) found that travel costs, travel time, and comfort are the most important factors for passenger route choices. However, because travel costs for plane transport are difficult to estimate, only travel time and a small aspect of comfort were included in this research.

Not all nodes are interconnected; therefore, a car network is included to represent, in some cases, the final leg of travel between a city and an airport. The study focuses on trains and planes, which is why cars are only used to connect cities and airports. While passengers can travel between two cities in Europe by car, it is unlikely they would fly from New York to Schiphol and then drive to Barcelona. For this reason and to simplify the model, car travel is not included on a large scale but is considered only as a means of reaching the airport.

With these networks established, it is time to calculate the likelihood that passengers will choose specific routes. This calculation is conducted in the block entitled Passenger route assignment (5.0).

The first step in block 5.0, is to determine the different routes passengers can take. These routes are searched by using the k-shortest path algorithm, during the search different penalties are added in the algorithm. These penaltie are needed to add realism in the model, a time penalty is added to the total travel time if a passenger makes a specific travel choice in his shortest path. The penalties and their reason can be found in Table 2.

From these routes, a top 5 will be created, which will then be compared with one another. In this comparison, a probability is assigned to each route. The probability is calculated by using the Random Regret method. This probability will then be multiplied by the number of passengers wishing to travel between the cities, allowing us to add the passengers to the different edges they travel.

| No. | Reason for the penalty | Between | Penalty Time |
|---|---|---|---|
| 1 | If an airport isn't a hub | Airport–Airport | +2 |
| 2 | If a taxi ride is taken to a city that isn't the city of the airport, and isn't the final destination | Airport–City – City | +10 |
| 3 | Access time airport with train | City–Airport (with HSR) | +2 |
| 4 | Access time airport with car | City–Airport (no HSR) | +3 |
| 5 | Egress time airport with train | Airport (with HSR)–City | +1.25 |
| 6 | Egress time airport with car | Airport (no HSR)–City | +0.75 |
| 7 | Air–Rail transfer at airport (no HSR) | Plane–Taxi–HSR | +1.5 |
| 8 | Air–Air transfer | Airport–Airport–Airport | +1 |

Table 2: Different penalties in the model

Once passengers are assigned to their edges, the network can be analyzed (block 6.0). The purpose of this analysis is to determine the values of various indicators. This will involve calculating CO2 emissions and examining the number of passengers travelling through each hub to ultimately provide advice to airports. Additionally, it will assess the difference in emissions generated per ban. After completing these steps, the base scenario is created. This base scenario can than be used to compare, with different scenario's in which the ban is implemented.

## B. Frequency-based reallocation method

The passenger data from Eurostat (2025) does not account for transfer passengers, leading to potential double counting in the OD matrix. To make sure the data accounts for transfer passengers, the Frequency-Based Reallocation Method was used. The method reallocates passengers based on the likelihood of transfers, aligning demand with actual origins and destinations.

The method is based on the following idea: If 70 passengers travel from hub A to hub B and 30 passengers travel from hub A to hub C, the probability of a passenger choosing the route to hub B is 70%, while the route to hub C is 30%. This reasoning is based on the principle that routes with more passengers are more attractive, as opposed to those with fewer. Additionally, higher passenger numbers often indicate greater supply. The main purpose of the method is to provide quick and easy insights into the choices of transfer passengers to estimate passenger flows. However, it is not suitable for precise predictions of transport flows. The formulas of the method are shown in Equation 1, 2, and 3.

**Frequency-based demand correction method**

$$N_{ij} + T_{ij} = D_{ij} \quad ,\forall i, j \in N \tag{1}$$

$$X_{ij} * (1 - (trans_j * Hub_j)) = N_{ij}, \forall i, j \in N \tag{2}$$

$$T_{ij} = \sum_{n \in N} X_{in} \cdot \text{trans}_n \cdot \text{Hub}_n \cdot \text{Fly}_{inj} \cdot \left( \frac{X_{nj}}{\sum_{m \in N} X_{nm} \cdot \text{Fly}_{inj} - X_{in}} \right), \forall i, j \in N \tag{3}$$

Where:

| Variable | Meaning |
|---|---|
| $N$ | Sets of airports where: $n, j, i \in N$ |
| $D_{ij}$ | Demand between city i and j |
| $T_{ij}$ | Passeners with a transfer traveling between city i and j |
| $N_{ij}$ | passengers traveling without a transfer between city i and j |
| $trans_i$ | Transfer rate at airport i |
| $Hub_i$ | 1 if airport i is a hub zero otherwise |
| $Fly_{i,j,n}$ | 1 if a passenger can transfer towards route n to j , after traveling on route i,n. Zero otherwise |

Formula Equation 1 expresses total demand $D_{ij}$ as the sum of direct passengers ($N_{ij}$) and transfers ($T_{ij}$). Direct demand is computed by removing transfers from the original OD entry (Equation 2). Transfers are estimated using hub status and transfer rates. Transfer passengers are reallocated based on the probability of continuing to another destination, as shown in Equation 3. This probability is the share of passengers on a given route relative to all outbound passengers—adjusted by two factors: (1) the feasibility of the transfer, using the Dynamic Restricted Area method (Appendix B), and (2) exclusion of the inbound flight from the probability base. The areas that are prohibit by the Dynamic Restricted Area method can be found in Table 3.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 3: Restricted areas after different flights

After calculating $N_{ij}$ and $T_{ij}$, the values are summed for each OD pair to obtain the $D_{ij}$. To maintain symmetry, the average of $D_{ij}$ and $D_{ji}$ together is used, resulting in an OD matrix that correctly accounts for transfer passengers. Figure 8 presents a small example that illustrates how the data is adjusted for transfer passengers. In this example, node C is a hub with a transfer rate of 0.4. The example aims to calculate how many passengers travel between airports A and E.

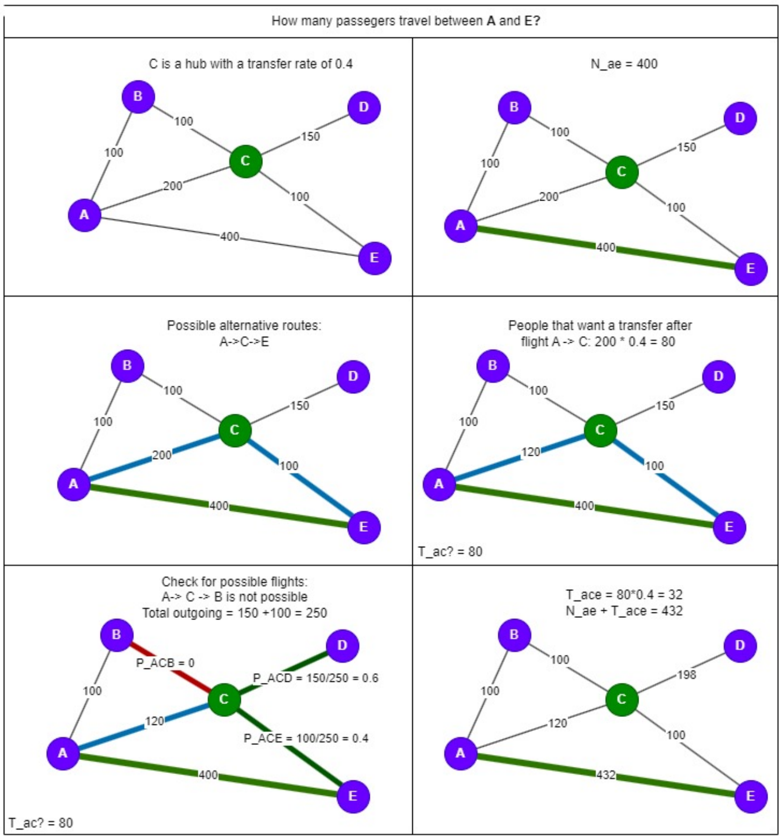


Figure 8: Example: Frequency-based reallocation method

## C. Random Regret method

When the routes are determined and penalties added, there are ultimately five fastest routes for passengers, to travel between two specific cities. With these possible options, it's time to calculate the mode choice using the Random Regret method (RRm). This method is not widely used in similar research, though it is sometimes employed by consultants. Its advantage lies in accounting for the regret passengers feel about unchosen options, unlike the MNL model, which evaluates each route independently without considering other choices. Additionally, the MNL model is challenging to apply when different route options are similar, making the RRm model more effective. Another benefit of this method is that it bases regret solely on the travel time required to complete the route, simplifying its application while accurately estimating the probability of someone choosing a specific route. The used formulas to calculate the RRm are shown in Equation 4 and 5. The only attribute included is the travel time, which is assigned a beta of 0.01. This beta is taken from the study of Grolle (2020), which used this beta for his City-to-City demand estimation.

**Random Regret formulas**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln \left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall r \in R \tag{4}$$

$$P(r) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R \tag{5}$$

Where:

| Variable | Meaning |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R$ | Set of all available route options |
| $P(r)$ | Change that route $r$ is chosen |

After the probabilities are calculated with the RRm, the passengers can be assigned towards the specific edges they are travelling on. The formula for assigning passengers is shown in Equation 6. At this stage, the probability of a passenger taking the route is multiplied by the number of passengers travelling between the two cities. The number of passengers for each route will then be allocated to the various edges it takes, and this will be done for all the routes. In the end, the number of people travelling over each specific edge will be known. The formula for this step is shown in Equation 6

**Allocation of passengers to different edges formula**

$$f(e) = \sum_{R \in \mathcal{R}_e} P_r \cdot \mathrm{OD}_{i,j}, \quad \forall\, i,j \in I, \tag{6}$$

Where:

| Variable | Meaning |
|---|---|
| $R$ | A specific route |
| $\mathcal{R}_e$ | Set of routes that pass through edge $e$ |
| $P_r$ | Probability of selecting route $R$ |
| $\mathrm{OD}_{i,j}$ | Number of passengers wanting to travel between city i and j |
| $e$ | An edge in the network |
| $f(e)$ | Total passenger flow assigned to edge $e$ |
| $I$ | Set of cities |

Once all passengers are assigned to different edges, this part of the algorithm is complete. From these calculations, a Link Load Matrix is generated, which can then be used to calculate the various indicators, in the policy analysis. This Link Load matrix consists of the amount passengers travelling on edges between different nodes within the network.

## D. Implementing the ban on short-haul flights

This study examines two methods for implementing a ban on short-haul flights: one based on the distance between airports and one based on the travel time compared to High-Speed Rail (HSR). The different scenario's for the ban are calculated using the same steps as the base scenario. Only in the network design (block 4.0 in Figure 7) are adjustments made to calculate the impact of the ban. In this step different travel times of prohibit routes is set to zere. So the k-shortest path algorithm doesn't consider these paths because they aren't there.

The distance-based ban is implemented using a pre-computed distance matrix between airports, that is made using the haversine method (block 1.0 in figure Figure 7). A flight is only permitted if the distance between the origin and destination exceeds a specified threshold $Dis_{ban}$. The total travel time $TT_{AB}$ is calculated as shown in Equation 7, and the ban indicator $Ban_{ab}$ determines whether a connection is allowed, as shown in the following equations:

**Distance-based ban calculations**

$$TT_{AB} = \left( \frac{dis_{AB}}{AVE_{ab}^{plane_{speed}}} + T_{taxi} \right) \cdot Ban_{ab} \tag{7}$$

$$Ban_{ab} = \begin{cases} 1, & \text{if } dis_{AB} \geq Dis_{ban} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}$ | Total flight time between airport A and Airport B in hours |
| $dis_{AB}$ | Distance between airport A and airport B in km |
| $Dis_{ban}$ | Distance based ban value in km |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |

The time-based ban compares the flight time to the fastest available HSR route between the city centers associated with the airports. Only EU-internal flights are considered. To allow fair comparison, airports are linked to nearby cities (within 50 km) using the Haversine formula (Equation 10–13). The model checks whether both airports are within range of cities that have HSR connections, using the conditions in Equation 14 and Equation 15. If the HSR journey time $TT_{X_AY_B}^{HSR}$ is shorter than a given threshold $T_{ban}$, the corresponding flight is banned. Otherwise, the flight is allowed or excluded based on the presence of nearby HSR-linked cities, as shown in Equation 16. The full formulation is as follows:

**Time-based ban calculations**

$$TT_{AB}^{Plane} = \left( \frac{d_{AB}}{AVE_{AB}^{plane_{speed}}} + T_{taxi} \right) \cdot Ban_{ab} \tag{9}$$

$$a_{AX} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_A) \cdot \cos(\phi_X) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{10}$$

$$a_{BY} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_B) \cdot \cos(\phi_Y) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{11}$$

$$d_{AX} = 2r \cdot \arcsin\left(\sqrt{a_{AX}}\right) \tag{12}$$

$$d_{BY} = 2r \cdot \arcsin\left(\sqrt{a_{BY}}\right) \tag{13}$$

$$dis_{AX} = \begin{cases} 1, & \text{if } d_{AX} \leq 50 \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

$$dis_{BY} = \begin{cases} 1, & \text{if } d_{BY} \leq 50 \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

$$Ban_{AB} = \begin{cases} 1, & \text{if } TT_{X_AY_B}^{HSR} \geq T_{ban} \\ 1 - (dis_{AX} \cdot dis_{BY}), & \text{otherwise} \end{cases} \tag{16}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}^{Plane}$ | Total flight time between airport A and Airport B in hours |
| $TT_{X_AY_B}^{HSR}$ | Travel time between connected city x to airport A and connected city y to airport B |
| $dis_{AX}$ | 1 if city X is in the service area of airport A |
| $T_{ban}$ | Time based ban value in hours |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight , 0 otherwise |
| $\phi_1, \phi_2$ | Latitudes of the two points (in radians) |
| $\Delta\phi$ | $\phi_2 - \phi_1$, difference in latitudes |
| $\Delta\lambda$ | $\lambda_2 - \lambda_1$, difference in longitudes |
| $r$ | Radius of the sphere (e.g., Earth's radius) |
| $a_{ax}$ | Intermediate value in the Haversine formula between airport a and city x |
| $d_{ax}$ | Great-circle distance between airport a and city x |

# IV. Policy scenario's and input data

section III has already discussed some of the assumptions of this study, but these are not all the assumptions. This chapter will address the last larger assumptions made in this study. The section will also discuss the different experimental scenarios that are compared with the base scenario.

## A. The correction of input data

The study used large data files from Eurostat (2025), which contain passengers carried on the routes flown from major hubs in Europe. The issue with the data is its size, leading to long calculation times. Therefore, unnecessary data was removed from the model for several reasons.

The first reason airports have been removed is the small flights between Turkish cities. These airports only had flights departing to Turkey. As the study focuses on the impact on the European Union, data from these flights are not relevant. Additionally, the ban will have no impact on these trips, making no difference in the final data. Therefore, it was decided to remove these domestic flights. This decision was also made for international flights from airports that only travelled to Turkey, as they are irrelevant for the same reason.

The dataset used in the study had several limitations and adjustments. Data from the UK dated back to 2019, while the rest was from 2023, due to the UK's departure from the EU in 2020, which ended its obligation to share such data. Unnecessary data was removed from the model, including airports with only flights to the UK and Turkey, as well as some Finnish airports used solely for domestic flights. The study also excluded some European cities to avoid complicating the model without improving the results. Consequently, airports that could not be linked to cities—often located on islands or in areas without high-speed rail stations—were removed to maintain passenger data integrity. Additionally, Soekarno-Hatta International Airport in Indonesia was excluded due to inaccurate data, which showed only one incoming flight when other sources indicated many more, potentially distorting the results.

### B. Emission parameter

To calculate average emissions per passenger, several choices were made. First, an average figure for all flight types was used. Figure 1 shows that long-haul flights emit more than short-haul flights. However, the number of passengers on short-haul flights is expected to fluctuate significantly, while this effect will remain small for long-haul flights. This study primarily focuses on the impact of the ban rather than on precise predictions of the outcomes if the ban is implemented. Therefore, an average number of CO2 emissions per passenger per kilometre was chosen.

The average emissions per passenger per kilometre are based on the emissions of a Boeing 737-400, from a study performed in 2008. This year was chosen due to the availability of data. This narrow-body aircraft has smaller engines and is primarily used for short-haul travel. The selected emission value is 115 g/passenger/km (Carbon Independent (2025)). Note that current aircraft are much cleaner due to innovations in recent years. But this study does not aim to determine an exact emissions figure and focuses solely on comparing CO2 emissions from aviation, after a ban is implemented. Therefore, the value of this data is not crucial for the conclusions.

### C. The design of the HSR infrastructure

Looking at Figure 9, it is noticeable that the European HSR network is not yet fully complete. Additionally, several important connections remain unestablished. Including this network in the study is therefore complicated. This situation necessitates examining the current state of each line and its future prospects.

To maintain simplicity in the study, it will be assumed that the HSR pathway is complete in Europe, this complete HSR network is based on the study of Grolle (2020) that tried to optimize the HSR network in Europe. Furthermore, airports with HSR stations that are not depicted in Figure 9 will also be included. The missing lines and connections between cities are based on the overview of Interrail-Eurail (2024)

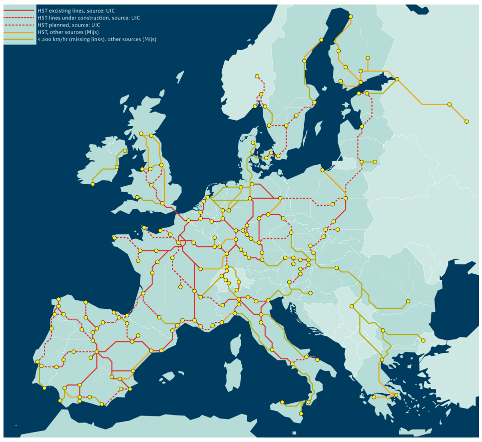


Figure 9: Current HSR network in Europe (Mijs (nd))

The HSR infrastructure used in this study is complete, meaning that all cities in Europe can be reached via HSR, though this does not apply to all airports. Additionally, the study does not consider timetables of train operators; therefore, the travel time of the HSR in the model is sometimes faster than in reality. While this is not true for all routes, it is a common aspect.

### D. Scenario's of the ban on short-haul flights

Currently, several companies and countries have implemented bans on short-haul flights (Wikipedia (2025)). The choice of different policy scenarios is based on the current actions taken by companies or countries. The chosen policy scenarios can be found in Table 4. The aim is to make both types of bans roughly equal. This has been done to ultimately compare which type of ban will be the most effective.

| Scenario | Time-based | Distance-based |
|---|---|---|
| Low | 2.5 hours | 250 km |
| Middle | 6 hours | 750 km |
| High | 14 hours | 1500 km |

Table 4: Different policy scenarios

Starting with the high scenario, the aim is to significantly intervene in the aviation market. This scenario proposes a complete ban on short-haul flights for both types of bans. Figure 1 noted that short-haul flights account for about 24% of total CO2 emissions. A complete ban on short-haul flights with the current HSR network should theoretically reduce emissions by at least 20%. This scenario allows to assess what impact a full ban has on the base scenario, where a full functional HSR network is implemented. With a time-based ban, CO2 reductions will properly be slightly lower than with a distance-based ban, as more routes are permitted under the time-based ban to consider possible alternatives.

For the middle scenario, its based on the study of Adler et al. (2010). According to a study by Adler et al. (2010), his research found that trains are faster than planes till a distance of 750 km. This distance is therefore an interesting benchmark. According to the theory that people always choose the fastest route, this suggests that at this point people should chose 50/50 between air or rail. The question then arises as to whether this holds true if passengers can also fly around the ban. So their can be expected that this scenario is one of the most optimal formats for the ban. The time-based ban will also represent a distance of 750 km. As this means that it would take approximately 6 hours for a person to cover 750 km. The six hours is found by desk research (Google (2025)) different routes, and look how long this takes.

The last and lowest scenario is based on the current policy in France (de Weert (2022)). France has enacted a law, approved by the EU, that bans flights within 2.5 hours of train travel. The purpose of this ban is to eliminate flights within an EU country, as these can be easily replaced by other modes of transport. According to Adler et al. (2010), high-speed rail (HSR) should be significantly faster over this distance. However, the ban can be relatively easy to circumvent. Therefore, it will be interesting to investigate whether this ban will ultimately achieve its intended effect. Desk research indicates that the distance-based ban in this scenario should be 250 km Google (2025).

# V. Verification & validation

This section addresses the verification and validation of the model through a case study using a smaller dataset of transported passengers, as the original model takes too long to run multiple tests. The parameters and track infrastructure are identical to those in the original model. The data used can be found in Appendix C.

Based on the case study results, this section verifies several aspects: the effect of the optimal HSR network, the performance of the reallocation method, and the effectiveness of the ban. It also validates the number of iterations used in the k-shortest path method and the influence of the value of k within this method.

## A. Verification of the HSR network

The model replaces air travel with a High-Speed Rail (HSR) network optimized to provide passengers with unrestricted route choices instead of relying on fixed train lines. This flexibility allows the model to simulate a fully functioning network. Verification was conducted using Google (2025) to compare real public transport times with the model's predictions, which are shown in Table 5. The comparison revealed that the model can predict quicker travel times in some cases, especially in Western Europe. These differences arise because the model does not account for real-world HSR infrastructure complexities, such as the absence of built infrastructure, train speeds, and HSR lines.

Although the model does not fully capture the nuances of real travel behavior, such as long transfer times or inter-station changes in cities like Paris, it generally predicts more favorable travel times for rail compared to reality. Consequently, the model overestimates the attractiveness of HSR, leading to a higher allocation of passengers to trains than would realistically occur. While this enhances the model's competitive positioning of rail over air travel, it also raises concerns about reliability of the model, as the predicted modal shifts are based on an idealized version of the network rather than actual infrastructure constraints.

| HSR-Route | Real time (hour) | Model time (hour) | Percentage difference |
|---|---|---|---|
| Amsterdam-Brussel | 2.3 | 1.88 | -18.26% |
| Amsterdam-Barcelona | 11.43 | 9.05 | -20.82% |
| Rome-Barcelona | No train option (17.41 bus option) | 7.21 | -58.59% |
| London-Amsterdam | 4.75 | 3.96 | -16.63% |
| Paris-Lille | 1.03 | 1.26 | +22.33% |
| Paris-Amsterdam | 3.38 | 3.76 | +11.24% |

Table 5: HSR travel times real vs model outcomes (Google (2025))

## B. Verification of the airport reallocation method

A new method has been designed to correct the input data form Eurostat (2025). Important variables from this method are the degrees from Table 3, which are used for the Dynamic Restricted Area. By adjusting various variables, the impact on different routes is examined to determine whether it is justified. The expectation of this test is that the number of passengers wishing to travel between two non-hubs will be significantly influenced by changes in the prohibited area indicators. Additionally, to verify the effectiveness of the frequency-based reallocation method, the direction of routes to the hub must always be negative relative to the input. If this occurs, it indicates that the method is functioning as intended. The results of this verification are shown in Table 6.

| Scenario | Abu Dhabi International Airport → London City | % Difference with Output | Abu Dhabi International Airport → Schiphol | % Difference with Input |
|---|---|---|---|---|
| Input | 0 | - | 197310.00 | - |
| Output | 13264.80 | - | 166508.01 | -15.61% |
| After longhaul flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After longhaul flight transfer to short-haul flight 360° | 11898.84 | -10.30% | 164442.70 | -16.66% |
| After medium flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After shorthaul flight transfer to shorthaul flight 0° | 2764.97 | -79.15% | 164953.30 | -16.40% |
| After shorthaul flight transfer to longhaul flight 360° | 1365.962315 | -89.70% | 163563.5915 | -17.10% |

Table 6: Sensitivity analysis: Restricted area algorithm

As expected, Table 6 shows significant changes in the route between the two non-hub airports. The results indicate that the number of passengers is greatly influenced by changes in the prohibited area. This illustrates that the size of the prohibited area can significantly impact the results of this method. It is difficult to determine whether the chosen values reflect reality, given the results and the fact that not all routes were included in the case study.

Examining the route between Schiphol and Abu Dhabi, it is evident that all values relative to the input are negative. This indicates that fewer people travel on this route, reallocating to other routes. This suggests that the method is functioning as intended. In conclusion, the Frequency-based reallocation method performs as expected, but the Dynamic Restricted Area significantly affects the outcomes.

## C. Validation the number of iterations

Several algorithms are used in this study. Because the shortest path algorithms can get stuck or repeat themselves, a maximum number of iterations was introduced. This allows for a maximum of x steps per route to find a faster option. The maximum is set at 1500 iterations in the base model, meaning that after 1500 steps, the model will proceed to the next route. To verify this number, runs with 500, 1000, 1500, 2000 and 2500 iterations were conducted in the smaller model to analyse sensitivity, the values from the base scenario are compared.

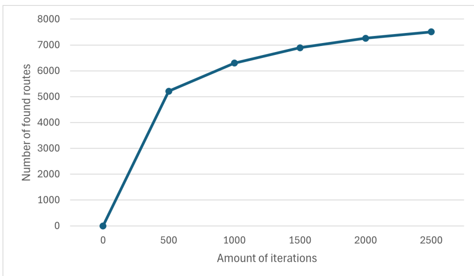


Figure 10: Increasing routes that are found by a higher number of iterations

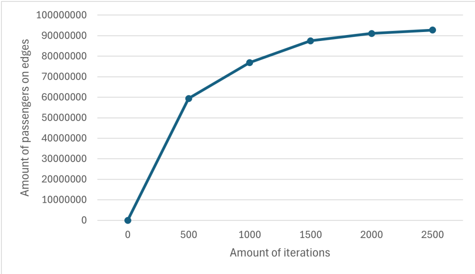


Figure 11: Stabilising number of passengers assigned to different edges with a greater number of iterations.

The issue with the number of iterations is that as it increases, the time required for the model to run rises sharply. Therefore, it is important to select an iteration number that maximizes estimates without significantly increasing the algorithm's computation time. Figure 10 shows that the number of new faster routes does not increase significantly beyond 1500 iterations, although it still rises after that point. This indicates that complex routes can still be found by the model after 1500 iterations. If these routes are selected, the total number of allocated passengers will increase sharply. However, Figure 11 shows that after 1500 iterations, there are not many additional passengers identified by the model. This suggests that while new routes can still be found after 1500 iterations, their usage is very low.

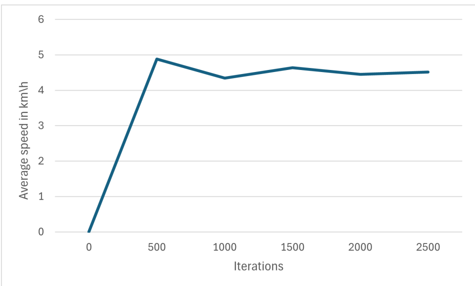


Figure 12: Stabilising average speed with a higher number of iterations.

Further validation using average travel speed was conducted to determine if the model was stuck in a local minimum. The results of this validation are shown in Figure 12. Despite continued increases in the number of iterations, the average speed between city pairs stabilizes around 1500 iterations, indicating that the fastest and most relevant routes have largely been identified by this point. It shows a local minimum at 1000 iterations.

In conclusion, with a limited number of iterations, not all possible solutions can be found. Increasing the iterations beyond 2500 will enhance the number of routes identified, allowing the model to better predict complex routes. After 1500 iterations, only a small group of people are assigned to the newly discovered routes, and hardly any faster routes are found. Therefore, 1500 iterations is sufficient for this study.

### D. Validation of the k value

Within the algorithm, various routes are considered. In the method, there was chosen to examine up to five different routes between cities. The question now is how significant the effect of these chosen routes is on the results. To assess this, different values for k and the total number of passengers assigned to the various edges are analysed.

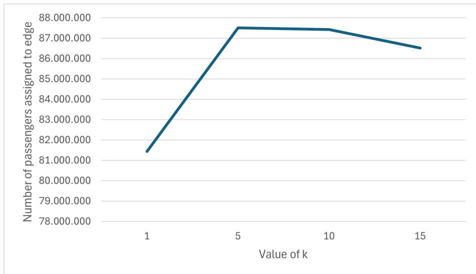


Figure 13: Validation of k-value with the number of assigned passengers

Looking at Figure 13, there is a noticeable difference between a k-value of 1 and 5. This indicates that significantly more complex routes are found, which is not necessarily a drawback. Comparing the k-values of 5 and 10, it can be observed that the increase in routes stabilises. While more routes are identified, this has little effect on the outcomes. Between k=10 and k=5, there is hardly any impact on the results. When k is increased, the results may even decline. This can be attributed to the fact that more routes are selected, causing them to compete for the same passengers. As there is a maximum number of passengers that can be distributed among the different routes, an increase in the number of routes also leads to the selection of longer routes. These longer routes compete with one another for passengers, resulting in a total decrease and making the outcomes appear less reliable. Thus, choosing a k-value of five is not inappropriate.

## VI. Results

This chapter presents the model's results. First, it examines passenger choices in the base case. Next, it compares the results of different scenarios with the base case, focusing on passenger choices for each scenario. It then discusses the impact of these choices on aviation CO2 emissions. Finally, it addresses the effects of the ban on various hubs.

### A. Results of the base scenario

Due to the absence of reference data, a base case was developed. This scenario can be compared with various scenarios where a ban on short-haul flights is in effect. The assessment of the base scenario considers the mode choices made by passengers found by the model, with results shown in Figure 14.

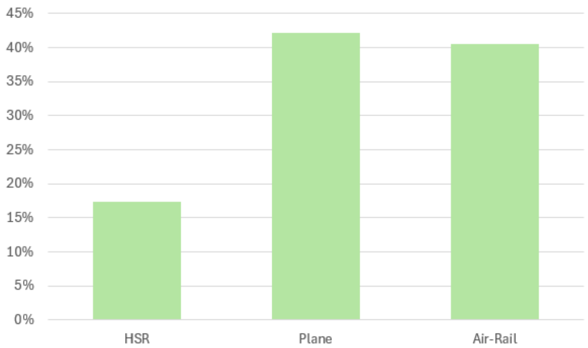


Figure 14: The choices of the passengers in the reference alternative were no ban is applied.

Looking at Figure 14, the key observation is that a group of passengers is already attributed to the HSR, which is noteworthy since the input data consists entirely of air passengers. As discussed earlier, one possible explanation is that this increase results from the presence of a well-functioning HSR infrastructure. This suggests that if the network performs optimally, a significant proportion of passengers traveling within Europe will choose the HSR. Additionally, the Air-Rail network is around 40% in the base scenario, indicating that a well-functioning HSR network can lead to an increase in Air-Rail passengers.

### B. Passenger mode choice with a ban on short-haul flights

The study compared six different bans on short-haul flights with the basescenario, investigating their impact on passenger behavior. In each scenario, the ban is implemented alongside a well-functioning HSR infrastructure in Europe. The results focus on overall modal choice and the effects on direct and transfer passengers, as illustrated in Figure 15 and 16.

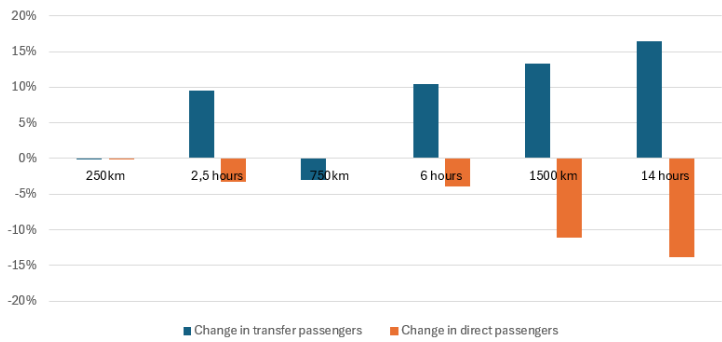


Figure 15: The difference between people choosing to travel directly or via transfer to their final destination, compared to the no-ban alternative.

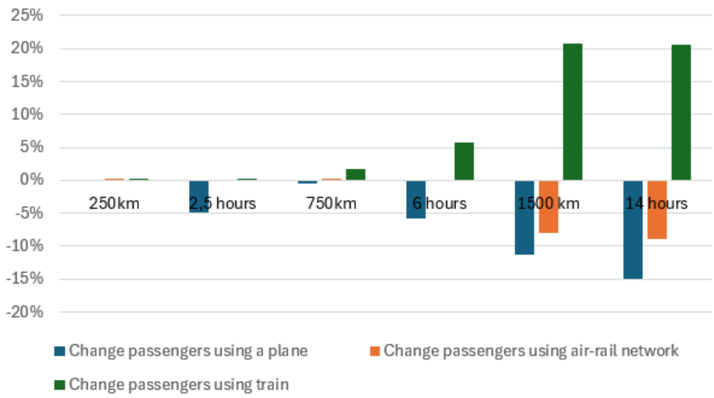


Figure 16: The difference in transport choices by alternative compared to the scenario where no ban applies.

In the 250 km distance-based ban, only minor behavioral changes are observed. A small group of passengers switches from air travel to rail, and there is a slight decrease in transfer passengers and direct passengers. In this scenario, many passengers have likely already switched to the HSR or Air-Rail alternative. This means that the 250 km ban shows little difference from the base scenario, except that the remaining passengers on really short flights are now forced to travel by HSR or take a direct flight. Also there is a small increase in Air-Rail passengers.

Under the 2.5-hour time-based ban, a clearer shift is visible. The number of passengers using high-speed rail (HSR) slightly increases, direct flights decrease, and transfer flights become more common. The number of Air-Rail passengers is slightly decreasing. Importantly, the use of planes decreases by 5% compared to the base scenario. This indicates that the 2.5-hour ban results in a small decrease in plane passengers and an increase in HSR use. However, only the direct use of HSR is growing, not the number of passengers using the Air-Rail network. It implies that passengers are not choosing the Air-Rail option but rather traveling around the ban. This is notable because the use of the Air-Rail network is declining, while the number of transfer passengers is rapidly increasing. The decline in Air-Rail use may be due to the existing fully functional HSR network, leading many passengers with the option of Air-Rail to choose this route already in the base scenario. When the ban has eliminated some routes in this scenario, is it logical that some passengers disappear.

Comparing the 250 km and 2.5-hour bans, it is evident that the 2.5-hour ban had a larger impact on mode choices than the 250 km ban. This effect is also observable when comparing the 750 km and 6-hour bans. In this case, the distance-based ban does not influence passenger choices, while the time-based ban has a larger impact on passenger mode choices.

Overall, the direction of the effects of all four scenarios is the same regarding mode choice. In all scenarios, the use of aircraft decreases while the use of HSR increases. Only the Air-Rail alternative shows differences; notably, the distance-based ban increases Air-Rail use, whereas the time-based ban decreases it. This may be because re-routing is more complicated under the distance-based ban, as there are fewer routes available. Consequently, it is likely faster for a passenger to take the HSR after a flight than to fly around the ban. So it seems that the flying distance of the detour influences passengers' choice behaviour. However, the average distance passengers have to detour was not determined in this study.

With the 750 km ban, passenger behaviour shifts different than the time-based alternatives. There is a reduction in transfers within Europe and increased HSR usage. Also the usage of Air-Rail is increasing slightly, but this is very limited. The 6-hour ban shows further growth in HSR usage, as seen in the 2.5-hour scenario. Additionally, the number of transfer passengers is increasing, with a small reduction in direct passengers. This indicates that some passengers are attempting to fly around the ban. This is likely easier in the 6-hour scenario than in the 750 km scenario because more flight paths remain available in the 6-hour scenario. In the 750 km scenario, there is a decrease in transfer passengers, indicating that it is more challenging to travel around the ban in that scenario.

The results of the 1500 km and 14-hour bans look very similar. Both show a decrease in direct passengers and an increase in transfer passengers. However, the time-based ban has a larger impact on passenger choices than the distance-based ban. This differs when examining mode choices, as the number of HSR passengers grows slightly more under the distance-based ban than under the time-based ban. Notably, the use of the Air-Rail network in both types of scenarios decreases by more than 5%, indicating that a ban on short-haul flights will reduce the use of the Air-Rail network, while passenger choices seem to be shifting toward the direct HSR alternative.

## C. The impact on CO2 emissions

To say something about the CO2 emissions of aviation after the introduction of a ban on short-haul flights, the average difference compared to the reference alternative was considered. Using these results, an attempt is made to illustrate the impact of various scenarios of the ban on CO2 emissions in the aviation market. Figure 17 shows the different result about the CO2 emissions.

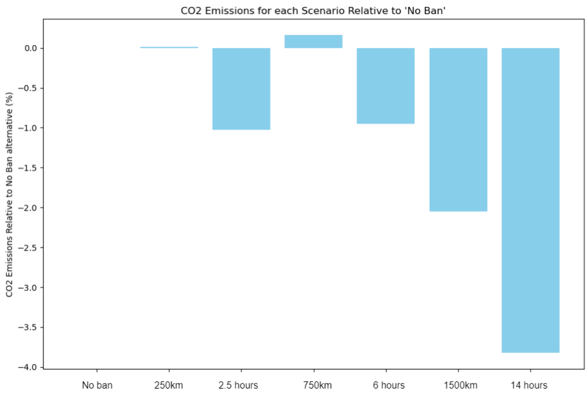


Figure 17: The difference in CO2 emissions based on the No Ban scenario, where no ban on short-haul flights is in place.

The first thing to notice is that when the ban is set at 250 km or 750 km, CO2 emissions do not decrease; in fact, they slightly increase compared to the base scenario. Examining passenger mode choices reveals that these two scenarios have little impact on mode selection. However, when comparing mode choices with CO2 emissions, it is evident that the group flying now takes larger detours, resulting in increased CO2 emissions. This is likely due to the design of the ban, as it does not consider possible HSR routes. As a result, a passenger may need to travel around the ban, likely increasing the flight distance they must cover. This suggests that a passenger's detour distance impacts CO2 emissions.

In the time-based scenarios, particularly the 2.5-hour and 6-hour bans, there is a slight decrease in aviation CO2 emissions. Notably, the 2.5-hour ban results in a greater reduction in CO2 than the 6-hour ban. In both time-based scenarios, the number of HSR passengers is increasing, suggesting that removing plane options on competitive HSR routes leads to a reduction in CO2 emissions. It is important to note that in the base scenario, a fully functional HSR network is used, so the train competes with planes on more routes than in reality.

Considering the two extreme alternatives, the 1500 km and 14-hour bans effectively eliminate short-haul flights. The reduction in CO2 emissions from aviation due to these bans is modest compared to the base scenario, yielding a maximum reduction of only 4% for the 14-hour ban, while the 1500 km scenario shows a reduction of 2%. This indicates that even with a fully functional HSR infrastructure, a complete ban has a limited impact on CO2 emissions. However, it may be that much of the CO2 emissions have already been reduced by the base case; as a result, the emission reductions due to the ban are relatively low. This indicates that, once a fully functioning HSR network is available in Europe, a ban on short-haul flights has a minimal effect on further reduction of CO2 emissions from aviation.

Revisiting the structure of both types of bans in the complete ban scenario, it can be observed that the time-based ban restricts fewer routes. Consequently, there are more flight options available to passengers, resulting in a shorter distance for rerouting. This is in contrast to the distance-based ban, which has a higher average detour distance and fewer transfer passengers. Since the time-based ban leads to a greater reduction in CO2 emissions, it is evident that a balance must be struck between the extent of the ban and the average detour distance for passengers. This variable is likely to have a more significant impact on CO2 reduction than the number of transfer passengers. The variable of average detour distance was not examined in this study.

## D. Impact of the ban on the different hubs

In addition to the overall CO2 picture, this study aimed to map the impact of the ban on various European airports, focusing on hubs. This was achieved by comparing the total departing passengers from the hubs in each scenario with the number from the base scenario. The effect on each hub was analyzed for each scenario, resulting in a global overview. This overview is illustrated in Figure 18, which displays the ban's effect on the different hubs.

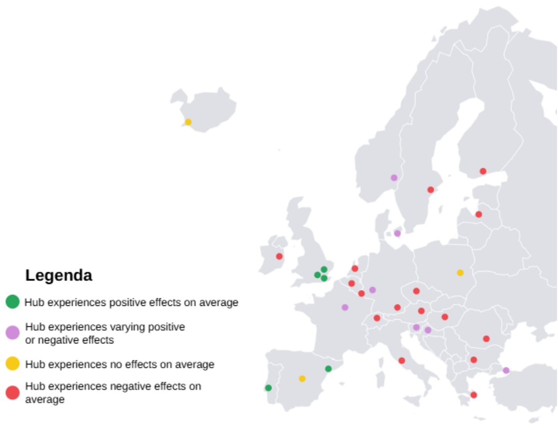


Figure 18: The average effect of the ban on different hubs around Europe.

The effects of various short-haul flight bans on airport hubs reveal significant variation compared to the base scenario. Smaller airports—such as Prague, Riga, Sofia, and Budapest—experience the most notable declines in passenger numbers under larger ban scenarios. While changes are minimal under a 250 km ban, greater distance- or time-based restrictions can lead to reductions in passenger volumes of up to 50% in some cases. These effects are especially evident at airports with limited intercontinental connections or smaller hubs.

In contrast, Ljubljana, another smaller airport, shows moderate passenger increases under specific scenarios but also significant decreases under certain time-based scenarios. This is likely due to the small input data, which increases the impact on this hub. Reykjavik-Keflavik remains largely unaffected across all scenarios, reflecting its geographic isolation and minimal exposure to short-haul traffic.

Larger hubs such as Schiphol, Frankfurt, and Munich initially experience growth in passenger numbers under moderate bans (250 km or 2.5-hour), likely due to their robust intercontinental networks and their role as transfer nodes, allowing passengers to bypass affected short-haul routes. However, with more extensive bans (e.g., 6-hour or 1,500 km), even these airports show declines compared to the base case. Regional context and geographic location also influence outcomes: southern airports like Barcelona and Madrid exhibit growth under most scenarios, possibly due to their peripheral location, which limits the number of affected routes. Non-EU hubs in London and Istanbul see moderate increases in passenger numbers compared to the base scenario. Overall, the analysis underscores that hub responses to short-haul bans are highly sensitive to location and previous connectivity prior to the ban.
Compared to the base scenario, it is evident that implementing a ban leads to a loss of passengers at several hubs within EU countries. On its own, this is not an issue, as the aim of the policy is to encourage more passengers to choose HSR. What is striking is that with any kind of ban, the EU can be divided into regions where one hub experiences an increase in passenger numbers while other hubs in the area lose passengers. This suggests that the location of a hub plays a significant role in the impact of the ban. If a hub's location allows it to maintain more flight routes, it tends to attract more passengers. The study did not examine how many routes a hub retains after the introduction of a ban, but it is noteworthy that hubs that have high connectivity in the base scenario in particular, experience an increase in some scenarios.

## VII. Conclusion

The aim of this study was to investigate how passenger mode choices would influence the impact of a ban on short-haul flights, assuming that the European HSR network is fully developed and functioning effectively. Previous research primarily focused on short trips and individuals wishing to travel within the distance of the ban. Therefore, this study also examined whether transfer passengers influence the impact of the ban and how hubs in Europe are affected by it. Finally, it investigated how the ban affects CO2 emissions from aviation in Europe. All of this was based on the following research question.

**How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?**

The study compared the ban with a baseline scenario in which a fully functional HSR network was constructed. This baseline scenario produced interesting results. The input data consisted entirely of airline passengers. The results showed that by optimising the HSR route, some passengers were already willing to use HSR as a mode of transport instead of aircraft. The proportion of passengers using the Air-Rail network also increased. Therefore, the results indicate that by improving the HSR network, some passengers would choose not to use an aircraft. However, this does not mean that the proportion willing to choose the optimised HSR network would actually make that choice. The study based passenger choices solely on travel time with minimal consideration for comfort; travel costs were not included. Furthermore, the effect of this optimisation on CO2 emissions compared to reality was not examined. The only conclusion that this research can draw in this area is that by optimising the HSR network, there is a good chance that a proportion of passengers will be prepared to use the HSR instead of the plane.

The ban on short-haul flights has been developed in two different ways in this research: a ban based on time and a ban based on distance. The results show that only the time-based ban results in a reduction in CO2 across all scenarios. With the distance-based ban, this only occurs with a complete ban on short-haul flights. This indicates that when there is a well-functioning HSR network in Europe, a time-based ban can still lead to a reduction in CO2 emissions from aviation. However, it has not been investigated whether this is also the case if the current HSR network is applied in the research.

Previous research paid little attention to the effect of transfer passengers on the impact of the ban on CO2 emissions. This research shows that these transfer passengers do influence the impact of the ban, particularly evident in the 250 km scenario. In this scenario, there is little change in passengers' choice behaviour, yet CO2 emissions from aviation still increase. As HSR use increases and direct passengers decrease, the results show that the increase in CO2 must be due by transfer passengers.

Examining the differences in behavioural choices of passengers under a time-based ban versus a distance-based ban reveals that a time-based ban leads to a faster growth in transfer passengers, while this is not the case with a distance-based ban. The research demonstrates that transfer passengers influence the impact of the ban on CO2 emissions from aviation, but this does not depend on the number of passengers, rather on the average distance a transfer passenger must cover due to the ban.

For the Air-Rail network, this research shows that by optimising the HSR network, utilisation of this network increases significantly. The study cannot confirm whether this is due to HSR stations at airports, but it is likely that this plays a role. At the time the ban is implemented, there will be little increase in passengers on the Air-Rail network. It is more likely that there will be a decrease in Air-Rail use. This does not have to be detrimental; if passengers switch to HSR, it can still lead to a reduction in CO2 emissions.

The impact of the ban varies among different hubs and depends on specific scenarios. Notably, the impact depends on the location and size of the airport before the ban is implemented. These two factors influence the connectivity of a hub when a ban on short-haul flights is enacted; a hub with high connectivity after the implementation of the ban has a greater chance of experiencing an increase in passenger numbers. This research cannot say whether the hubs will disappear due to the ban, but it does indicate that the impact on some hubs could be significant.

In conclusion, this study shows that when Europe has a well-functioning HSR network, a time-based ban on short-haul flights can still lead to a small reduction in CO2. The impact of this ban is influenced by the route choices of transfer passengers and the distances they must detour. Air-Rail use will not significantly increase when the ban is implemented if a good HSR network is already in place, it is more likely to decrease. Additionally, the ban will have a considerable negative impact on passenger numbers in several smaller hubs within EU member states, but whether these hubs will also disappear remains uncertain. Thus, a ban on short-haul flights will affect the EU, but it is questionable whether this impact is desirable.

## VIII. Discussion & Future research

This study is the first to use this method to predict passengers' behavioral choices during a ban on short-haul flights. The method primarily focused on passengers' transfer times, excluding travel costs. The findings indicate that when a well-functioning high-speed rail (HSR) network exists in Europe, some passengers are willing to choose HSR. However, it remains uncertain whether this holds true when travel costs are factored in. In order to get a good picture of the effects of the ban on Europe in the presence of a well-functioning HSR network, it remains therefore still relevant to examine how travel costs influence passenger choices.

This study assumes that a well-functioning HSR network is being developed in Europe. Using a baseline scenario in which this network has been established, different scenarios have been compared. Previous research by Baumeister and Leung (2020) indicated that a study in Finland, where a ban was implemented, would result in a 95% reduction in CO2 emissions in the transport sector. In Baumeister and Leung (2020) study, the possible alternatives for passenger transport consisted of the existing national train network. When comparing this study with Baumeister and Leung (2020) findings, it can be argued that a ban on short-haul flights would reduce CO2 emissions in the aviation sector in Europe. However, this will be influenced by transfer passengers, which could result in an increase in CO2 emissions due to the ban. While Baumeister and Leung (2020) study suggests that a ban on short-haul flights could significantly affect CO2 emissions in the transport sector, this study indicates that, if the ban is implemented at a European level, transfer passengers may negatively affect CO2 emissions. As this study does not utilise the current HSR or train network, it remains unclear how the reduction in CO2 emissions would be. It may therefore be worthwhile to repeat this study using the existing HSR network in Europe.

The study shows that transfer passengers influence the effectiveness of the ban on short-haul flights. To determine which type or size of ban will positively impact Europe, the study revealed that this depends not on the number of transfer passengers but on the average distance they must detour. While the number of transfer passengers may still play a role, it is less significant than distance. This study identified a connection between these two variables and the overall CO2 reduction resulting from the ban. The results are considered logical and do not indicate to come from an error in the model. Therefore, it can be expected that the average detour distance of transfer passengers will also play a role in reality. It may still be worthwhile to explore the relationship between the average detour distance of transfer passengers and the number of transfer passengers in a potential follow-up study. This could help identify which type and size of the ban would lead to a reduction in CO2 emissions in Europe. The expectation is that if these two variables are balanced, a scenario can be found that maximises CO2 reduction if a ban on short-haul flights is implemented in Europe.

In Europe, the ban appears to redistribute passengers, particularly affecting smaller hubs. The study indicates that fewer passengers will travel from various European hubs, leading to decreased turnover at these hubs and raising concerns about the potential disappearance of some. It is clear that the ban will impact hubs, and future research should examine how this will affect different regions connectivity and economical.

### A. The limitations of the model

The study had two major limitations that could have affected the results. The first was the lack of available data on passenger demand between different cities. To estimate how many passengers wanted to travel between cities, data from Eurostat (2025) was used, indicating the number of passengers who travelled between two airports in 2023. The issue with this data is that it does not account for transfer passengers, leading to double counting. To allocate these transfer passengers to their original departure and destination, the Frequency-based reallocation method was employed.

The Frequency-base reallocation method was specifically developed for this study and has not been used before in existing literature. However, it only considers departing passengers and potential illogical transfers, neglecting other possible factors. For instance, passengers may choose specific airlines or alliances. If an airline operates a hub-and-spoke strategy, the likelihood that a passenger will fly to the airline's home hub is significantly higher than on the largest route departing from a specific airport. Therefore, it would be beneficial for future research to explore whether these airlines or alliances can influence the frequency-based reallocation method to better explain passenger travel behaviour.

Another major limitation of this study was the computing power used to calculate the algorithm. To minimise computing time, a maximum number of iterations was set for the k-shortest path algorithm. Consequently, the algorithm could not calculate all possible route options. As a result, some more complicated routes for passengers may not have been identified, leading to an overestimation of the number of passengers using certain routes. When interpreting the data, it is important to recognise that this model did not predict a future scenario that corresponds 100 per cent to reality.

### B. Future research

Based on the discussion and conclusion, several suggestions have been identified that may be worth investigating in future research. Below is a list of the various suggestions for future research arising from this study.

- What is the average detour distance for transfer passengers when a ban on short-haul flights is implemented in Europe?
- How will the ban on short-haul flights impact CO2 emissions in aviation, assuming the current HSR infrastructure is used as an alternative?
- How will travel costs influence passenger choices when the HSR infrastructure is optimally developed?
- What are the economic consequences for hub regions when a ban on short-haul flights is implemented in Europe?
- How can airline routes be incorporated into the frequency-based reallocation method?

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# Appendix A Hub information

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source transfer-ratings |
|---|---|---|---|---|---|
| Amsterdam (Schiphol) | EHAM | 36.3% | Yes | 75 min | Schiphol Airport (2024) |
| Brussels | EBBR | 14% | Yes | 75 min | Brussels Airport (2023) |
| Munich | EDDM | 45% | No | 90 min | Munchen Airport (2024) |
| Sofia | LBSF | 0.9% | No | 90 min | Sofia Airport (2023) |
| Zagreb | LDZA | **0.9%** | No | 90 min | Based on Sofia airport |
| Vienna | LOWW | 22.41% | Yes | 75 min | Flughafen Wien (2024) |
| Prague | LKPR | **0.9%** | No | 90 min | Based on Sofia |
| Copenhagen | EKCH | 21.67% | Yes | 75 min | Copenhagen Airport (2024) |
| Helsinki (Finavia) | EFHK | 10.92% | No | 90 min | Finavia (2024) |
| Paris (Charles de Gaulle) | LFPG | 20% | Yes | 75 min | Groupe ADP (2024) |
| Frankfurt (Fraport) | EDDF | 50% | Yes | 75 min | Fraport (2024) |
| Athens (Athens Intl) | LGAV | 18.6% | Yes | 75 min | Athens International Airport (2024) |
| Budapest (Ferenc Liszt) | LHBP | **0.4%** | Yes | 75 min | Based on NACO |
| Reykjavik-Keflavik | BIKF | 27% | No | 90 min | Isavia (2024) |
| Dublin | EIDW | 3.4% | No | 90 min | DAAgroup (2024) |
| Rome-Fiumicino | LIRF | **22.41%** | Yes | 75 min | Based on Flughafen Wien (2024) |
| Riga | EVRA | **0.9%** | Yes | 75 min | Based on Sofia |
| Luxembourg | ELLX | **0.9%** | No | 90 min | Based on Sofia |
| Warsaw-Chopin | EPWA | 26% | No | 90 min | Warsaw Chopin Airport (2024) |
| Lisbon | LPPT | **20%** | No | 90 min | ACI (2024) based on Rome and Athens airport |
| Bucharest-Henri Coandă | LROP | **0.9%** | No | 90 min | Based on Sofia |
| Ljubljana | LJLJ | **0%** | No | 90 min | Based on the possible routes and airlines |
| Madrid | LEMD | **33%** | No | 90 min | Based on NACO |
| Stockholm-Arlanda | ESSA | **7%** | Yes | 75 min | Based on 0.5 * Brussels airport |
| Barcelona | LEBL | **4.9%** | No | 90 min | Based on NACO |

Table 7: Information about major hubs in the European Union

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source |
|---|---|---|---|---|---|
| Istanbul | LTFM | **58.1%** | No | 90 min | Based on NACO |
| Oslo | ENGM | **13%** | Yes | 75 min | Based on NACO |
| Zurich | LSZH | 29.7% | No | 90 min | Zurich Airport (2024) |
| London Gatwick | EGKK | **14%** | No | 90 min | Based on Brussels |
| London Heathrow | EGLL | **24.6%** | No | 90 min | Based on NACO |
| London Stansted | EGSS | **7%** | No | 90 min | Based on Stockholm airport |

Table 8: Information about major hubs outside the European Union (highligted numbers are estimated)

# Appendix B Dynamic Restricted Area

This study uses a Frequency-based reallocation method, which examines the probability that a person will switch to another route. To make this method more realistic, a control is needed that checks whether a switch is logical. The Dynamic Restricted Area method is used for this purpose. This appendix provides a detailed explanation of how this method works, illustrated with an example. The formulas for this method can be found in **??**.

## A Example

To explain the method, an example will be used. This example involves a passenger who just arrived at Schiphol Airport after a flight from Athens. The passenger wants to transfer to a new flight, and the question is which route is available for the transfer. From Schiphol, the passenger has three possible options: Abu Dhabi, London, and New York. The coordinates (latitude and longitude) of these locations are listed in Table 9.

| **Airport** | **Latitiude** | **Longitude** |
|---|---|---|
| Schiphol | 52.3086 | 4.76389 |
| Eleftherios Venizelos International Airport | 37.93640137 | 23.94449997 |
| John F Kennedy International Airport | 40.6398 | -73.7789 |
| Sharjah International Airport | 24.433 | 54.6511 |
| London Heathrow Airport | 51.4706 | -0.19028 |

Table 9: Locations of the different airports for the example

The first step to check which transfers make sense is to evaluate the distance the passenger has already traveled and the distance to any new locations. This information helps determine whether the flight is long-haul, medium-haul, or short-haul, which is crucial for the next step. The distance is calculated using the Haversine formula. After calculating the distances,the flights are categorized.

| **From** | **To** | **Distance (km)** | **Type of flight** |
|---|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 2176 | Medium-haul flight |
| Schiphol | JFK (John F. Kennedy) | 5857 | Long-haul flight |
| Schiphol | Sharjah | 5161 | Long-haul flight |
| Schiphol | London Heathrow | 370 | Short-haul flight |

Table 10: Type of flights and distances between the airports

After calculating the distance and labelling the flights, it is time to examine the specific routes and the size of the area that prohibits passengers from transferring. In the study, this was achieved by assigning specific circle sizes to flight sequence types. Table 11 provides a small example of how this table should be interpreted. First, the flight that the passenger took to reach the hub is considered. In this example, the passenger arrived at Schiphol after departing from Athens, which is classified as a medium-haul flight. A possible option for the passenger is to transfer to JFK. Table 10 indicates that the flight from Schiphol to JFK is a long-haul flight. Adding these two flight types together, Table 11 shows that the variable $\theta_{i,n,j}^{restricted}$ takes the value of 90. This means that the prohibited area is

90 degrees wide, making it illogical for the passenger to transfer to a flight within a 90-degree radius of the flight between Schiphol and Athens.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 11: Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow JFK$

In addition to the transfer to JFK, this example also offers the option of transferring to Sharjah. For this flight, the variable $\theta_{i,n,j}^{restricted}$ is identical to that for the transfer to JFK. However, the transfer to Heathrow is different. The flight between Schiphol and London is a short-haul flight, while the other is a long-haul flight. Consequently, the variable $\theta_{i,n,j}^{restricted}$ must assume a different value. This value can be found in Table 12, resulting in a final value of zero for the variable $\theta_{i,n,j}^{restricted}$.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 12: Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow Heathrow$

The final step of the preparation is to calculate the direction of the various routes. This direction is determined using the Azimuth formula. When applied to the example, the results shown in Table 13 and 14.

| **From** | **To** | $\theta_{i,n}(^\circ)$ |
|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 322 |

Table 13: Direction of the route between Athens and Schiphol

| **From** | **To** | $\theta_{n,j}(^\circ)$ | $\theta_{i,n,j}^{restricted}$ $(^\circ)$ |
|---|---|---|---|
| Schiphol | JFK (John F. Kennedy) | 292 | 90 |
| Schiphol | Sharjah | 118 | 90 |
| Schiphol | London Heathrow | 250 | 0 |

Table 14: Direction and the restricted area for possible transfers after the flight from Athens to Schiphol is taken

The ultimate goal of this method is to assign the variable $Fly_{i,n,j}$ a value of 1 or 0. This value can be used in the Frequency-based demand correction method. To determine whether $Fly_{i,n,j}$ should be 1 or 0, the area where the passenger is not allowed to transfer must first be calculated. Equation 17, 18, 19, 20 and 21 are used for this calculation.

**Formulas Dynamic restricted area calculations:**

$$Fly_{i,n,j} = \begin{cases} 1, & \text{if } \theta^{start\_restiction}_{i,n,j} \leq \theta_{n,j} \leq \theta^{end\_restriction}_{i,n,j}, when: \theta^{start\_restiction}_{i,n,j} \leq \theta^{end\_restriction}_{i,n,j} \\ 1, & \text{if } \theta^{start\_restiction}_{i,n,j} \geq \theta_{n,j} \geq \theta^{end\_restriction}_{i,n,j}, when: \theta^{start\_restiction}_{i,n,j} \geq \theta^{end\_restriction}_{i,n,j} \\ 0, & \text{otherwist} \end{cases} \tag{17}$$

$$\theta^{margin}_{i,n,j} = \frac{\theta^{restricted}_{i,n,j}}{2} \tag{18}$$

$$\theta^{correction}_{i,n} = (\theta_{i,n} - 180) \mod 360 \tag{19}$$

$$\theta^{start\_restiction}_{i,n,j} = (\theta^{correction}_{i,n} - \theta^{margin}_{i,n,j}) \mod 360 \tag{20}$$

$$\theta^{end\_restriction}_{i,n,j} = (\theta^{correction}_{i,n} + \theta^{margin}_{i,n,j}) \mod 360 \tag{21}$$

Where:

| Variable | Meaning |
|---|---|
| $\theta_{i,n}$ | Flying direction between airport i and n |
| $\theta^{start\_restiction}_{i,n,j}$ | Start of the restriction for route i,n,j |
| $\theta^{end\_restriction}_{i,n,j}$ | End of the restriction for route i,n,j |
| $\theta^{restricted}_{i,n,j}$ | The size of the restricted area for route i,n,j |

The formulas first calculate the size of the margin in 18, which is used to determine the start and end points of the ban. Equation 19 then examines the opposite direction of the first flight, as it is necessary to ensure that the passenger does not travel back along their original route. Once this is established, the start and end points of the ban can be calculated using Equation 20 and 21 by adding and subtracting the margin from the corrected direction of travel of the first flight. Equation 17 first checks whether the start point is smaller than the end point. This is essential because the calculations are based on a circular system; if the value exceeds 360 degrees, the count restarts at 0 degrees. When the end point exceeds 360 degrees, the start and end points must be interpreted differently. Once all this is completed, one can check whether the direction $\theta_{n,j}$ of the potential transfer route falls within the forbidden area. If it does, the variable $Fly_{i,n,j}$ is assigned the value zero; otherwise, it is assigned the value one.

To complete the example illustrated in this Appendix, the following calculations need to be made, as shown below. For the route $Athens \rightarrow Schiphol \rightarrow JFK$, Figure 19 has been created to clarify the calculations.

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow JFK$ **and** $Athens \rightarrow Schiphol \rightarrow Sharjah$

$$\theta^{margin}_{Athens,Schiphol,Sharjah} = \theta^{margin}_{Athens,Schiphol,JFK} = \frac{90}{2} = 45$$

$$\theta^{correction}_{Athens,Schiphol} = 322 - 180 = 142$$

$$\theta^{start\_restiction}_{Athens,Schiphol,Sharjah} = \theta^{start\_restiction}_{Athens,Schiphol,JFK} = 142 - 45 = 97$$

$$\theta^{end\_restriction}_{Athens,Schiphol,Sharjah} = \theta^{end\_restriction}_{Athens,Schiphol,JFK} = 142 + 45 = 187$$

$$Fly_{Athens,Schiphol,JFK} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,JFK} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 1$$

$$Fly_{Athens,Schiphol,Sharjah} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,Sharjah} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 0$$

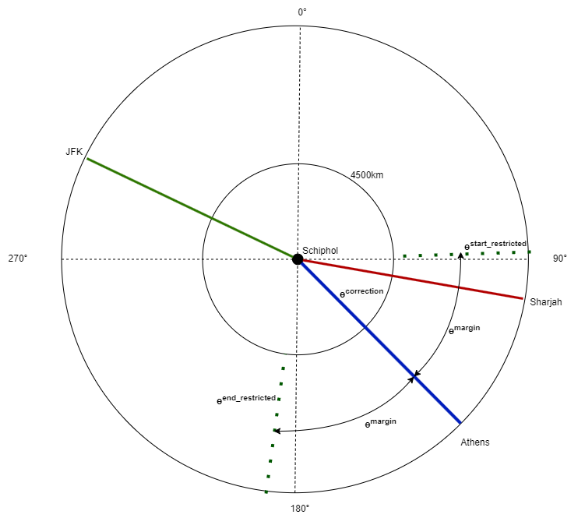


Figure 19: Example illustration if the transfer to the routes $Schiphol \rightarrow JFK$ and $Schiphol \rightarrow Sharjah$ is possible

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow Heathrow$

$$\theta^{half\_restricted}_{Athens,Schiphol,Heathrow} = \frac{0}{2} = 0$$

$$\theta^{correction\_angle}_{Athens,Schiphol} = 322 - 180 = 142$$

$$\theta^{start\_restiction}_{Athens,Schiphol,Heathrow} = 142 - 0 = 142$$

$$\theta^{end\_restriction}_{Athens,Schiphol,Heathrow} = 142 + 0 = 142$$

$$Fly_{Athens,Schiphol,Heathrow} = \begin{cases} \mathbf{1}, & \text{if } 142 \leq \theta_{Schiphol,Heathrow} \leq 142 \\ 0, & \text{otherwist} \end{cases} = 1$$

Finally, if the calculations for the Dynamic Restricted Area are complete, it means that a passenger arriving from Athens and wishing to transfer at Schiphol would logically transfer to London Heathrow or JFK. A transfer to Sharjah does not make sense and will therefore not be possible.

# Appendix C Information about the case study

This appendix is about the case study performed in the validation and verification section. In the appendix different information about the case study will be given.
The case study is designed to be completely identical to the main study. This means that all steps and parameters are the same, with the only difference being the input data. A small selection of different routes has been incorporated into the system, as detailed in Table 15. The choice of routes is based on the premise that various aspects can be investigated and tested. For instance, routes to Istanbul and London have been included, as well as routes to more remote areas of Europe. As shown in the table, the centre of the routes is at Schiphol and Frankfurt. This allows for a close examination of the reactions of hubs when processing the algorithm. Routes to countries outside the EU have also been added to assess whether passengers can utilise the hub and spoke network.

Table 15: Arrival and Departure Airports in the small model used to validate the algoritme

| **Departure Airport** | **Arrival Airport** |
|---|---|
| AMSTERDAM/SCHIPHOL airport | ABU DHABI INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | BARCELONA/EL PRAT airport |
| AMSTERDAM/SCHIPHOL airport | BOLOGNA/BORGO PANIGALE airport |
| AMSTERDAM/SCHIPHOL airport | BRUSSELS airport |
| AMSTERDAM/SCHIPHOL airport | BUDAPEST/LISZT FERENC INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | DUBLIN airport |
| AMSTERDAM/SCHIPHOL airport | FRANKFURT/MAIN airport |
| AMSTERDAM/SCHIPHOL airport | KOBENHAVN/KASTRUP airport |
| AMSTERDAM/SCHIPHOL airport | LONDON GATWICK airport |
| AMSTERDAM/SCHIPHOL airport | LONDON HEATHROW airport |
| AMSTERDAM/SCHIPHOL airport | LONDON/CITY airport |
| AMSTERDAM/SCHIPHOL airport | LUXEMBOURG airport |
| AMSTERDAM/SCHIPHOL airport | NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. airport |
| AMSTERDAM/SCHIPHOL airport | PARIS-CHARLES DE GAULLE airport |
| AMSTERDAM/SCHIPHOL airport | ROMA/FIUMICINO airport |
| AMSTERDAM/SCHIPHOL airport | SINGAPORE/CHANGI airport |
| AMSTERDAM/SCHIPHOL airport | STOCKHOLM/ARLANDA airport |
| AMSTERDAM/SCHIPHOL airport | VALENCIA airport |
| AMSTERDAM/SCHIPHOL airport | VENEZIA/TESSERA airport |
| BARCELONA/EL PRAT airport | LONDON GATWICK airport |
| BARCELONA/EL PRAT airport | LONDON HEATHROW airport |
| BARCELONA/EL PRAT airport | PARIS-CHARLES DE GAULLE airport |
| BARCELONA/EL PRAT airport | ROMA/FIUMICINO airport |
| BRUSSELS airport | ABU DHABI INTERNATIONAL airport |
| BRUSSELS airport | ATHINAI/ELEFTHERIOS VENIZELOS airport |
| BRUSSELS airport | DUBLIN airport |
| BRUSSELS airport | ISTANBUL/SABIHA GOKCEN airport |
| BRUSSELS airport | OSLO/GARDERMOEN airport |
| DUBLIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | BOLOGNA/BORGO PANIGALE airport |
| FRANKFURT/MAIN airport | DUBLIN airport |
| FRANKFURT/MAIN airport | ISTANBUL/SABIHA GOKCEN airport |
| FRANKFURT/MAIN airport | LONDON GATWICK airport |
| FRANKFURT/MAIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | LONDON/CITY airport |
| FRANKFURT/MAIN airport | ROMA/FIUMICINO airport |
| FRANKFURT/MAIN airport | TRIESTE/RONCHI DEI LEGIONARI airport |
| FRANKFURT/MAIN airport | VENEZIA/TESSERA airport |
| FRANKFURT/MAIN airport | VERONA/VILLAFRANCA airport |
| ISTANBUL/SABIHA GOKCEN airport | ABU DHABI INTERNATIONAL airport |
| MUENCHEN airport | AMSTERDAM/SCHIPHOL airport |
| MUENCHEN airport | NAPOLI/CAPODICHINO airport |
| MUENCHEN airport | PARIS-CHARLES DE GAULLE airport |
| MUENCHEN airport | RIGA airport |
| MUENCHEN airport | SINGAPORE/CHANGI airport |
| MUENCHEN airport | WIEN-SCHWECHAT airport |
| NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. Airport | LONDON HEATHROW airport |
| ROMA/FIUMICINO airport | DUBLIN airport |
| ROMA/FIUMICINO airport | ISTANBUL/SABIHA GOKCEN airport |

# B

# Formula sheet

This appendix presents the various formulas used in this research, displayed in the order they were developed in the algorithm.

## B.1. Airport data correction for transfer passengers formulas

**Frequency-based demand correction method**

$$N_{ij} + T_{ij} = D_{ij} \qquad \forall i,j \in N \tag{B.1}$$

$$X_{ij} * (1 - (trans_j * Hub_j)) = N_{ij} \qquad \forall i,j \in N \tag{B.2}$$

$$\sum_{n \in N} X_{in} * trans_n * Hub_n * (\frac{X_{n,j}}{(\sum_{m \in N} X_{nm} * Fly_{i,n,j}) - X_{in}})) * Fly_{i,n,j} = T_{ij} \qquad \forall i,j \in N \tag{B.3}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $N$ | Sets of airports where: $n, j, i \in N$ |
| $D_{ij}$ | Demand between city i and j |
| $T_{ij}$ | Passeners with a transfer traveling between city i and j |
| $N_{ij}$ | passengers traveling without a transfer between city i and j |
| $trans_i$ | Transfer rate at airport i |
| $Hub_i$ | 1 if airport i is a hub zero otherwise |
| $Fly_{i,j,n}$ | 1 if a passenger can transfer towards route n to j, after traveling on route i,n. Zero otherwise |

**Haversine formula**

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cdot\cos(\phi_2)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$d = 2r \cdot \arcsin\left(\sqrt{a}\right)$$

**Azimuth formula**

$$\theta_{in} = \arctan 2\left(\sin(\Delta\lambda)\cdot\cos(\phi_2), \cos(\phi_1)\cdot\sin(\phi_2) - \sin(\phi_1)\cdot\cos(\phi_2)\cdot\cos(\Delta\lambda)\right)$$

**Dynamic restricted area formula**

$$Fly_{i,n,j} = \begin{cases} 1, & \text{if } \theta^{start\_restiction}_{i,n,j} \leq \theta nj \leq \theta^{end\_restriction}_{i,n,j}, when: \theta^{start\_restiction}_{i,n,j} \leq \theta^{end\_restriction}_{i,n,j} \\ 1, & \text{if } \theta^{start\_restiction}_{i,n,j} \geq \theta nj \geq \theta^{end\_restriction}_{i,n,j}, when: \theta^{start\_restiction}_{i,n,j} \geq \theta^{end\_restriction}_{i,n,j} \\ 0, & \text{otherwist} \end{cases}$$

$$\theta^{half\_restricted}_{i,n,j} = \frac{\theta^{restricted}_{i,n,j}}{2}$$

$$\theta^{correction\_angle}_{i,n} = (\theta_{i,n} - 180) \mod 360$$

$$\theta^{start\_restiction}_{i,n,j} = (\theta^{correction\_angle}_{i,n} - \theta^{half\_restricted}_{i,n,j}) \mod 360$$

$$\theta_{i,n,j}^{end\_restriction} = (\theta_{i,n}^{correction\_angle} + \theta_{i,n,j}^{half\_restricted}) \mod 360$$

Where:

| Variable | Meaning |
|---|---|
| $\phi_1, \phi_2$ | Latitudes of the two points (in radians) |
| $\lambda_1, \lambda_2$ | Longitudes of the two points (in radians) |
| $\Delta\phi$ | $\phi_2 - \phi_1$, difference in latitudes |
| $\Delta\lambda$ | $\lambda_2 - \lambda_1$, difference in longitudes |
| $r$ | Radius of the sphere (e.g., Earth's radius) |
| $a$ | Intermediate value in the Haversine formula |
| $d$ | Great-circle distance between the two points |
| $\theta_{i,n}$ | Flying direction between airport i and n |
| $\theta_{i,n,j}^{start\_resticion}$ | Start of the restriction for route i,n,j |
| $\theta_{i,n,j}^{end\_restriction}$ | End of the restriction for route i,n,j |
| $\theta_{i,n,j}^{restricted}$ | The size of the restricted area for route i,n,j |

# B.2. City to City demand estimation formulas

**Utility function**

$$U_{i,x,y,j}^{fp} = \alpha_1 \cdot \left(t_{i,x}^{acs} + t_{i,x}^{acs} \cdot BB_{i,x}\right) + \alpha_2 \cdot \left(t_{y,j}^{egr} + t_{y,j}^{egr} \cdot BB_{y,j}\right) + \alpha_3 \cdot t_{x,y}^{DST} \tag{B.4}$$

$$p(m) = \frac{e^{-U_{i,x,y,j}^{fp}}}{\sum_{l \in R} e^{-U_{i,x,y,j}^{fp}}}, \quad \forall\, r \in R \tag{B.5}$$

Where:

| Variable | Meaning |
|---|---|
| $t_{i,x}^{acs}$ | Access time between $v_i$ and $ap_x$, |
| $t_{y,j}^{egr}$ | Egress time between $ap_y$ and $v_j$, |
| $BB_{i,x}$ | Border barrier between $v_i$ and $ap_x$; (0 if same country, else 1), |
| $BB_{y,j}$ | Border barrier between $ap_y$ and $v_j$; (0 if same country, else 1), |
| $t_{x,y}^{DST}$ | Displaced schedule time for route between $ap_x$ and $ap_y$; $\left(\frac{1}{4}\right.$ of headway $\left.h_{x,y}\right)$ . |
| $p(m)$ | Change that route m is chosen |

**Random regret equations**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln\left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall\, r \in R_{eu} \tag{B.6}$$

$$P(m) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R_{eu} \tag{B.7}$$

Where:

| Variable | Meaning |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R_{eu}$ | Set of all available route options that start and end in Europe |
| $P(m)$ | Change that route $m$ is chosen |

**Line Potential Determination**

$$MS_{i,j}^{\text{air, est}} = P(m) \tag{B.8}$$

$$\text{Potential}_{i,x,y,j} = MS_{i,j}^{\text{air, est}} \cdot \left(\frac{v_i^{\text{pop}} \cdot v_j^{\text{pop}}}{DS_{i,j}^{\text{road}} \,/\, f_{\text{car}}^{\text{detour}}}\right) \cdot p(m) \tag{B.9}$$

Where:

| Variable | Meaning |
|---|---|
| $Potential_{i,x,y,j}$ | Represents a relative number of passengers that would like to take the flight from $ap_x$ to $ap_y$ When travelling between cities $v_i$ and $v_j$ |
| $MS_{i,j}^{air,est}$ | Indicates the change of passengers that would opt for a flying option |
| $v_i^{pop}$ | Population of city $i$ |
| $DS_{i,j}^{road}$ | Distance between city i and city j |
| $f_{car}^{detour}$ | Detour factor car |

**Marketshare calculation**

$$\text{Marketshare}_{i,x,y,j} = \frac{\text{Potential}_{i,x,y,j}}{\sum_{i \in V^{2.5}} \sum_{j \in V^{2.5}} (\text{Potential}_{i,x,y,j})} \tag{B.10}$$

**City city demand calculation**

$$DM_{i,j}^{\text{air}} = \sum_x \sum_y \left(\text{Marketshare}_{i,x,y,j} \times N_{x,y}^{\text{pax}}\right) \quad \forall \quad x, y \in AP \tag{B.11}$$

Where:

| | |
|---|---|
| $DM_{i,j}^{air}$ | The amount of passengers traveling between city i and j |
| $Marketshare_{i,x,y,j}$ | The market share on route i,x,y,h |
| $N_{x,y}^{pax}$ | The amount of passengers travelling on edge x and y |

# B.3. The formulas used to build the ban on short-haul flights

**Distance-based ban calculations**

$$TT_{AB} = ((dis_{AB}/AVE_{ab}^{plane_{speed}}) + T_{taxi}) * Ban_{ab} \tag{B.12}$$

$$Ban_{ab} = \begin{cases} 1, & \text{if } dis_{AB} >= Dis_{ban} \\ 0, & \text{otherwist} \end{cases} \tag{B.13}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}$ | Total flight time between airport A and Airport B in hours |
| $dis_{AB}$ | Distance between airport A and airport B in km |
| $Dis_{ban}$ | Distance based ban value in km |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |

**Time-based ban calculations**

$$TT_{AB}^{Plane} = ((d_{AB}/AVE_{AB}^{plane_{speed}}) + T_{taxi}) * Ban_{ab} \tag{B.14}$$

$$a_{AX} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_A) \cdot \cos(\phi_X) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{B.15}$$

$$a_{BY} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_B) \cdot \cos(\phi_Y) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{B.16}$$

$$d_{AX} = 2r \cdot \arcsin\left(\sqrt{a}\right) \tag{B.17}$$

$$d_{BY} = 2r \cdot \arcsin\left(\sqrt{a}\right) \tag{B.18}$$

$$dis_{AX} = \begin{cases} 1, & \text{if } d_{AX} \text{ <= 50} \\ 0, & otherwise \end{cases} \tag{B.19}$$

$$dis_{BY} = \begin{cases} 1, & \text{if } d_{BY} \text{ <= 50} \\ 0, & otherwise \end{cases} \tag{B.20}$$

$$Ban_{AB} = \begin{cases} 1, & \text{if } TT^{HSR}_{X_A Y_B} >= T_{ban} \\ 1 - (d_{AX} * d_{BY}), & \text{otherwist} \end{cases} \tag{B.21}$$

Where:

| Variable | Meaning |
|---|---|
| $TT^{Plane}_{AB}$ | Total flight time between airport A and Airport B in hours |
| $TT^{HSR}_{X_A Y_B}$ | Travel time between connected city x to airport A and connected city y to airport B |
| $dis_{AX}$ | 1 if city X is in the service area of airport A |
| $T_{ban}$ | Time based ban value in hours |
| $AVE^{plane_{speed}}_{ab}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |
| $\phi_1, \phi_2$ | Latitudes of the two points (in radians) |
| $\Delta\phi$ | $\phi_2 - \phi_1,$ difference in latitudes |
| $\Delta\lambda$ | $\lambda_2 - \lambda_1,$ difference in longitudes |
| $r$ | Radius of the sphere (e.g., Earth's radius) |
| $a_{ax}$ | Intermediate value in the Haversine formula between airport a and city x |
| $d_{ax}$ | Great-circle distance between airport a and city x |

**Random Regret formula**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln\left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall\, r \in R \tag{B.22}$$

$$P(m) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R \tag{B.23}$$

Where:

| Variable | Meaning |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R$ | Set of all available route options |
| $P(m)$ | Change that route $m$ is chosen |

**Assignment of passengers towards there specific edge**

$$f(e) = \sum_{R \in \mathcal{R}_e} P_r \cdot \text{OD}_{i,j}, \quad \forall\, i, j \in I \tag{B.24}$$

Where:

| Variable | Meaning |
|---|---|
| $R$ | a route |
| $\mathcal{R}_e$ | set of routes that pass through edge $e$ |
| $P_r$ | probability of selecting route $R$ |
| $\text{OD}_{i,j}$ | number of passengers wanting to travel between city i and j |
| $e$ | an edge in the network |
| $f(e)$ | total passenger flow assigned to edge $e$ |
| $I$ | Set of cities |

## B.4. Formulas for policy analysis

**Formula to calculate the CO2 emissions**

$$TE_q = \sum_{e \in \mathcal{E}_{\dashv \rangle \triangledown}} f_e * AE_{air}, \quad \forall\, q \in Q \tag{B.25}$$

Where:

| Variable | Meaning |
|---|---|
| $Q$ | Set of different scenarios |
| $TE$ | Total emissions of airplanes in Europe |
| $AE_{air}$ | Average emissions per passenger per flight km |

# C
# Dynamic Restricted Area

This study uses a Frequency-based reallocation method, which examines the probability that a person will switch to another route. To make this method more realistic, a control is needed that checks whether a switch is logical. The Dynamic Restricted Area method is used for this purpose. This appendix provides a detailed explanation of how this method works, illustrated with an example. The formulas for this method can be found in Appendix B.

## C.1. Example

To explain the method, an example will be used. This example involves a passenger who just arrived at Schiphol Airport after a flight from Athens. The passenger wants to transfer to a new flight, and the question is which route is available for the transfer. From Schiphol, the passenger has three possible options: Abu Dhabi, London, and New York. The coordinates (latitude and longitude) of these locations are listed in Table C.1.

| Airport | Latitiude | Longitude |
|---|---|---|
| Schiphol | 52.3086 | 4.76389 |
| Eleftherios Venizelos International Airport | 37.93640137 | 23.94449997 |
| John F Kennedy International Airport | 40.6398 | -73.7789 |
| Sharjah International Airport | 24.433 | 54.6511 |
| London Heathrow Airport | 51.4706 | -0.19028 |

**Table C.1:** Locations of the different airports for the example

The first step to check which transfers make sense is to evaluate the distance the passenger has already traveled and the distance to any new locations. This information helps determine whether the flight is long-haul, medium-haul, or short-haul, which is crucial for the next step. The distance is calculated using the Haversine formula. After calculating the distances, Table 1.1 is used to categorise the different routes as specific types of flights.

| From | To | Distance (km) | Type of flight |
|---|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 2176 | Medium-haul flight |
| Schiphol | JFK (John F. Kennedy) | 5857 | Long-haul flight |
| Schiphol | Sharjah | 5161 | Long-haul flight |
| Schiphol | London Heathrow | 370 | Short-haul flight |

**Table C.2:** Type of flights and distances between the airports

After calculating the distance and labelling the flights, it is time to examine the specific routes and the size of the area that prohibits passengers from transferring. In the study, this was achieved by assigning specific circle sizes to flight sequence types. Table C.3 provides a small example of how this table should be interpreted. First, the flight that the passenger took to reach the hub is considered. In this example, the passenger arrived at Schiphol after departing from Athens, which is classified as a medium-haul flight. A possible option for the passenger is to transfer to JFK. Table C.2 indicates that the flight from Schiphol to JFK is a long-haul flight. Adding these two flight types together, Table C.3 shows that the variable $\theta_{i,n,j}^{restricted}$ takes the value of 90. This means that the prohibited area is 90 degrees wide, making it illogical for the passenger to transfer to a flight within a 90-degree radius of the flight between Schiphol and Athens.

| Before transfer type of flight | After transfer type of flight | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

**Table C.3:** Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow JFK$

In addition to the transfer to JFK, this example also offers the option of transferring to Sharjah. For this flight, the variable $\theta_{i,n,j}^{restricted}$ is identical to that for the transfer to JFK. However, the transfer to Heathrow is different. The flight between Schiphol and London is a short-haul flight, while the other is a long-haul flight. Consequently, the variable $\theta_{i,n,j}^{restricted}$ must assume a different value. This value can be found in Table C.4, resulting in a final value of zero for the variable $\theta_{i,n,j}^{restricted}$.

| Before transfer type of flight | After transfer type of flight | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

**Table C.4:** Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow Heathrow$

The final step of the preparation is to calculate the direction of the various routes. This direction is determined using the Azimuth formula. When applied to the example, the results shown in Table C.5 and C.6.

| From | To | $\theta_{i,n}(°)$ |
|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 322 |

**Table C.5:** Direction of the route between Athens and Schiphol

| From | To | $\theta_{n,j}(°)$ | $\theta_{i,n,j}^{restricted}$ (°) |
|---|---|---|---|
| Schiphol | JFK (John F. Kennedy) | 292 | 90 |
| Schiphol | Sharjah | 118 | 90 |
| Schiphol | London Heathrow | 250 | 0 |

**Table C.6:** Direction and the restricted area for possible transfers after the flight from Athens to Schiphol is taken

The ultimate goal of this method is to assign the variable $Fly_{i,n,j}$ a value of 1 or 0. This value can be used in the Frequency-based demand correction method. To determine whether $Fly_{i,n,j}$ should be 1 or 0, the area where the passenger is not allowed to transfer must first be calculated. Equation C.1, C.2, C.3, C.4 and C.5 are used for this calculation.

**Formulas Dynamic restricted area calculations:**

$$Fly_{i,n,j} = \begin{cases} 1, & \text{if } \theta_{i,n,j}^{start\_restiction} \leq \theta_{n,j} \leq \theta_{i,n,j}^{end\_restriction}, when: \theta_{i,n,j}^{start\_restiction} \leq \theta_{i,n,j}^{end\_restriction} \\ 1, & \text{if } \theta_{i,n,j}^{start\_restiction} \geq \theta_{n,j} \geq \theta_{i,n,j}^{end\_restriction}, when: \theta_{i,n,j}^{start\_restiction} \geq \theta_{i,n,j}^{end\_restriction} \\ 0, & \text{otherwist} \end{cases} \tag{C.1}$$

$$\theta_{i,n,j}^{margin} = \frac{\theta_{i,n,j}^{restricted}}{2} \tag{C.2}$$

$$\theta_{i,n}^{correction} = (\theta_{i,n} - 180) \mod 360 \tag{C.3}$$

$$\theta_{i,n,j}^{start\_restiction} = (\theta_{i,n}^{correction} - \theta_{i,n,j}^{margin}) \mod 360 \tag{C.4}$$

$$\theta_{i,n,j}^{end\_restriction} = (\theta_{i,n}^{correction} + \theta_{i,n,j}^{margin}) \mod 360 \tag{C.5}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $\theta_{i,n}$ | Flying direction between airport i and n |
| $\theta_{i,n,j}^{start\_restiction}$ | Start of the restriction for route i,n,j |
| $\theta_{i,n,j}^{end\_restriction}$ | End of the restriction for route i,n,j |
| $\theta_{i,n,j}^{restricted}$ | The size of the restricted area for route i,n,j |

The formulas first calculate the size of the margin in C.2, which is used to determine the start and end points of the ban. Equation C.3 then examines the opposite direction of the first flight, as it is necessary to ensure that the passenger does not travel back along their original route. Once this is established, the start and end points of the ban can be calculated using Equation C.4 and C.5 by adding and subtracting the margin from the corrected direction of travel of the first flight. Equation C.1 first checks whether the start point is smaller than the end point. This is essential because the calculations are based on a circular system; if the value exceeds 360 degrees, the count restarts at 0 degrees. When the end point exceeds 360 degrees, the start and end points must be interpreted differently. Once all this is completed, one can check whether the direction $\theta_{n,j}$ of the potential transfer route falls within the forbidden area. If it does, the variable $Fly_{i,n,j}$ is assigned the value zero; otherwise, it is assigned the value one.

To complete the example illustrated in this Appendix, the following calculations need to be made, as shown below. For the route $Athens \rightarrow Schiphol \rightarrow JFK$, Figure C.1 has been created to clarify the calculations.

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow JFK$ **and** $Athens \rightarrow Schiphol \rightarrow Sharjah$

$$\theta_{Athens,Schiphol,Sharjah}^{margin} = \theta_{Athens,Schiphol,JFK}^{margin} = \frac{90}{2} = 45$$

$$\theta_{Athens,Schiphol}^{correction} = 322 - 180 = 142$$

$$\theta_{Athens,Schiphol,Sharjah}^{start\_restiction} = \theta_{Athens,Schiphol,JFK}^{start\_restiction} = 142 - 45 = 97$$

$$\theta_{Athens,Schiphol,Sharjah}^{end\_restriction} = \theta_{Athens,Schiphol,JFK}^{end\_restriction} = 142 + 45 = 187$$

$$Fly_{Athens,Schiphol,JFK} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,JFK} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 1$$

$$Fly_{Athens,Schiphol,Sharjah} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,Sharjah} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 0$$

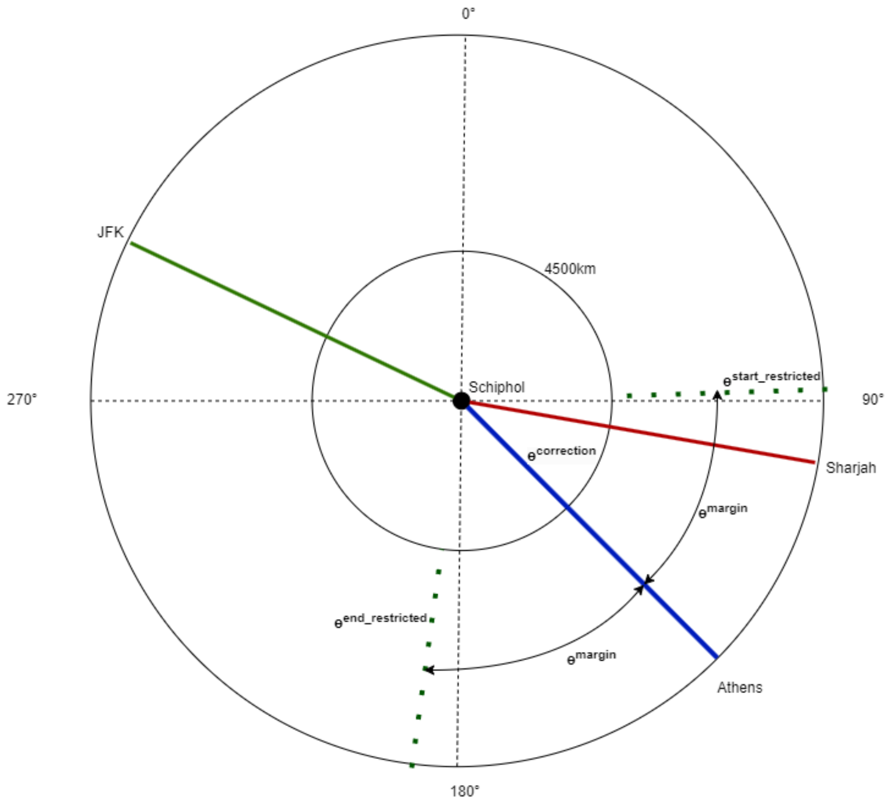


**Figure C.1:** Example illustration if the transfer to the routes $Schiphol \rightarrow JFK$ and $Schiphol \rightarrow Sharjah$ is possible

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow Heathrow$

$$\theta^{half\_restricted}_{Athens,Schiphol,Heathrow} = \frac{0}{2} = 0$$

$$\theta^{correction\_angle}_{Athens,Schiphol} = 322 - 180 = 142$$

$$\theta^{start\_restiction}_{Athens,Schiphol,Heathrow} = 142 - 0 = 142$$

$$\theta^{end\_restriction}_{Athens,Schiphol,Heathrow} = 142 + 0 = 142$$

$$Fly_{Athens,Schiphol,Heathrow} = \begin{cases} \mathbf{1}, & \text{if } 142 \leq \theta_{Schiphol,Heathrow} \leq 142 \\ 0, & \text{otherwist} \end{cases} = 1$$

Finally, if the calculations for the Dynamic Restricted Area are complete, it means that a passenger arriving from Athens and wishing to transfer at Schiphol would logically transfer to London Heathrow or JFK. A transfer to Sharjah does not make sense and will therefore not be possible.

# D

# Removed airports

This appendix provides an overview of the removed data for this study. The data comes from Eurostat (2025) and consists of information on passengers departing from a hub to all other airports. The data is from 2023, except for that of the United Kingdom, which is from 2019. This is because data from England is no longer updated in Eurostat since the UK has left the EU. Several airports and their associated routes have been removed from the data for various reasons.

## Domestic Flights in Turkey to Small Cities

This is a list of airports in Turkey that only have routes to Istanbul. Since this falls outside EU legislation, these data are not relevant to the study. Therefore, it was decided to remove it.

- LTFO – Afyon Airport
- LTFH – Samsun-Çarşamba Airport
- LTFG – Gazipaşa-Alanya Airport
- LTFE – Milas–Bodrum Airport
- LTFD – Balıkesir Airport
- LTDA – Iğdır Airport
- LTCW – Siirt Airport
- LTCV – Şırnak Airport
- LTCU – Muş Airport
- LTCT – Batman Airport
- LTCS – Mardin Airport
- LTCR – Şanlıurfa GAP Airport
- LTCP – Adıyaman Airport
- LTCO – Erzincan Airport
- LTCN – Kahramanmaraş Airport
- LTCM – Sinop Airport
- LTCK – Kars Harakani Airport
- LTCJ – Ağrı Airport
- LTCI – Van Ferit Melen Airport
- LTCG – Ordu–Giresun Airport
- LTCF – Elazığ Airport
- LTCE – Erzurum Airport
- LTCD – Malatya Erhaç Airport
- LTCC – Diyarbakır Airport
- LTCB – Bingöl Airport
- LTCA – Uşak Airport
- LTAZ – Nevşehir Kapadokya Airport
- LTAY – Denizli Çardak Airport
- LTAW – Tokat Airport
- LTAT – Afyon Airport
- LTAP – Amasya Merzifon Airport

## Flights Only via Istanbul

This is a list of airports that had routes to Istanbul. The list includes airports outside of Turkey, but since Turkey is not a member of the EU, this does not affect the final result. Therefore, it was decided to remove these airports.

- URMM – Mineralnye Vody Airport, Russia
- UTDD – Dushanbe International Airport, Tajikistan
- RPLL – Ninoy Aquino International Airport, Philippines
- OAKB – Kabul International Airport, Afghanistan
- OPKZ – Peshawar International Airport, Pakistan
- OISS – Shiraz International Airport, Iran
- OIMM – Mashhad International Airport, Iran
- OITT – Tabriz International Airport, Iran
- ORER – Erbil International Airport, Iraq
- ORBI – Baghdad International Airport, Iraq
- ORMM – Basra International Airport, Iraq
- UTAA – Ashgabat International Airport, Turkmenistan
- OEMA – Medina Airport, Saudi Arabia
- OEDF – King Fahd International Airport, Saudi Arabia
- OMSJ – Sharjah International Airport, UAE
- VNKT – Tribhuvan International Airport, Nepal
- VGHS – Hazrat Shahjalal International Airport, Bangladesh
- ZMCK – Chinggis Khaan International Airport, Mongolia
- HEBA – Borg El Arab Airport, Egypt
- HTDA – Julius Nyerere International Airport, Tanzania

## Flights Only via London

This list comprises airports that exclusively operate routes to London. Given that London is located in the United Kingdom, which is no longer a member of the European Union, it has been determined that these airports with the specified routes should be excluded, as their removal will not significantly affect the results.

- VAAH – Sardar Vallabhbhai Patel International Airport, India
- VOHS – Rajiv Gandhi International Airport, India
- VCBI – Bandaranaike International Airport, Sri Lanka
- VGZR – Hazrat Shahjalal International Airport, Bangladesh
- WBSB – Brunei International Airport, Brunei
- YPPH – Perth Airport, Australia
- YSSY – Sydney Kingsford Smith Airport, Australia
- GVBA – Nelson Mandela International Airport, Cape Verde
- TBPB – Grantley Adams International Airport, Barbados
- TLPL – Hewanorra International Airport, St. Lucia
- TAPA – V. C. Bird International Airport, Antigua
- MKJS – Sangster International Airport, Jamaica
- MKJP – Norman Manley International Airport, Jamaica
- KAUS – Austin–Bergstrom International Airport, USA
- KMSY – Louis Armstrong New Orleans International Airport, USA
- EGJJ – Jersey Airport, UK
- EGJB – Guernsey Airport, UK
- EIKN – Ireland West Airport Knock, Ireland

## Only Domestic Flights Without Alternatives

This list comprises airports that focus exclusively on domestic flights. There are no alternatives to these airports, and no nearby cities are included in the study. Therefore, it was decided to exclude these airports from the study.

- EFRO – Rovaniemi Airport, Finland
- EFIV – Ivalo Airport, Finland
- EFKT – Kittilä Airport, Finland
- EFKU – Kuopio Airport, Finland

## No Nearby Cities in Study

This is a list of airports not connected to a city in the study, as not all cities were included. Since passengers do not have a final destination, it was decided to exclude these airports from the study.

- LEAS – Asturias Airport, Spain
- LECO – A Coruña Airport, Spain
- LEST – Santiago de Compostela Airport, Spain
- LXGB – Gibraltar International Airport, Gibraltar
- LEAM – Almería Airport, Spain
- LGKR – Corfu International Airport, Greece
- LGPZ – Aktion National Airport, Greece
- LICR – Reggio Calabria Airport, Italy
- LICA – Lamezia Terme International Airport, Italy
- EKRN – Bornholm Airport, Denmark
- EPCY – Częstochowa-Rudniki Airport, Poland
- EPBY – Bydgoszcz Ignacy Jan Paderewski Airport, Poland
- EFVA – Vaasa Airport, Finland
- EYKA – Kaunas Airport, Lithuania
- LRSV – Suceava Airport, Romania
- LRTR – Timi□oara Traian Vuia International Airport, Romania
- LROD – Oradea International Airport, Romania
- LGMK – Mykonos Airport, Greece
- LGSA – Chania International Airport, Greece
- LBWN – Varna Airport, Bulgaria
- LEMG – Málaga Airport, Spain
- BGSF – Kangerlussuaq Airport, Greenland

## Special Case

This last airport was removed because the data towards this airport was incomplete. Therefore it could not be included in this research.

- WIII – Soekarno–Hatta International Airport, Indonesia

# E

# Information about the case study

This appendix is about the case study performed in chapter 5. In the appendix different information about the case study will be given.

The case study is designed to be completely identical to the main study. This means that all steps and parameters are the same, with the only difference being the input data. A small selection of different routes has been incorporated into the system, as detailed in Table E.1. The choice of routes is based on the premise that various aspects can be investigated and tested. For instance, routes to Istanbul and London have been included, as well as routes to more remote areas of Europe. As shown in the table, the centre of the routes is at Schiphol and Frankfurt. This allows for a close examination of the reactions of hubs when processing the algorithm. Routes to countries outside the EU have also been added to assess whether passengers can utilise the hub and spoke network.

| Departure Airport | Arrival Airport |
|---|---|
| AMSTERDAM/SCHIPHOL airport | ABU DHABI INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | BARCELONA/EL PRAT airport |
| AMSTERDAM/SCHIPHOL airport | BOLOGNA/BORGO PANIGALE airport |
| AMSTERDAM/SCHIPHOL airport | BRUSSELS airport |
| AMSTERDAM/SCHIPHOL airport | BUDAPEST/LISZT FERENC INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | DUBLIN airport |
| AMSTERDAM/SCHIPHOL airport | FRANKFURT/MAIN airport |
| AMSTERDAM/SCHIPHOL airport | KOBENHAVN/KASTRUP airport |
| AMSTERDAM/SCHIPHOL airport | LONDON GATWICK airport |
| AMSTERDAM/SCHIPHOL airport | LONDON HEATHROW airport |
| AMSTERDAM/SCHIPHOL airport | LONDON/CITY airport |
| AMSTERDAM/SCHIPHOL airport | LUXEMBOURG airport |
| AMSTERDAM/SCHIPHOL airport | NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. airport |
| AMSTERDAM/SCHIPHOL airport | PARIS-CHARLES DE GAULLE airport |
| AMSTERDAM/SCHIPHOL airport | ROMA/FIUMICINO airport |
| AMSTERDAM/SCHIPHOL airport | SINGAPORE/CHANGI airport |
| AMSTERDAM/SCHIPHOL airport | STOCKHOLM/ARLANDA airport |
| AMSTERDAM/SCHIPHOL airport | VALENCIA airport |
| AMSTERDAM/SCHIPHOL airport | VENEZIA/TESSERA airport |
| BARCELONA/EL PRAT airport | LONDON GATWICK airport |
| BARCELONA/EL PRAT airport | LONDON HEATHROW airport |
| BARCELONA/EL PRAT airport | PARIS-CHARLES DE GAULLE airport |
| BARCELONA/EL PRAT airport | ROMA/FIUMICINO airport |
| BRUSSELS airport | ABU DHABI INTERNATIONAL airport |
| BRUSSELS airport | ATHINAI/ELEFTHERIOS VENIZELOS airport |
| BRUSSELS airport | DUBLIN airport |
| BRUSSELS airport | ISTANBUL/SABIHA GOKCEN airport |
| BRUSSELS airport | OSLO/GARDERMOEN airport |
| DUBLIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | BOLOGNA/BORGO PANIGALE airport |
| FRANKFURT/MAIN airport | DUBLIN airport |
| FRANKFURT/MAIN airport | ISTANBUL/SABIHA GOKCEN airport |
| FRANKFURT/MAIN airport | LONDON GATWICK airport |
| FRANKFURT/MAIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | LONDON/CITY airport |
| FRANKFURT/MAIN airport | ROMA/FIUMICINO airport |
| FRANKFURT/MAIN airport | TRIESTE/RONCHI DEI LEGIONARI airport |
| FRANKFURT/MAIN airport | VENEZIA/TESSERA airport |
| FRANKFURT/MAIN airport | VERONA/VILLAFRANCA airport |
| ISTANBUL/SABIHA GOKCEN airport | ABU DHABI INTERNATIONAL airport |
| MUENCHEN airport | AMSTERDAM/SCHIPHOL airport |
| MUENCHEN airport | NAPOLI/CAPODICHINO airport |
| MUENCHEN airport | PARIS-CHARLES DE GAULLE airport |
| MUENCHEN airport | RIGA airport |
| MUENCHEN airport | SINGAPORE/CHANGI airport |
| MUENCHEN airport | WIEN-SCHWECHAT airport |
| NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. Airport | LONDON HEATHROW airport |
| ROMA/FIUMICINO airport | DUBLIN airport |
| ROMA/FIUMICINO airport | ISTANBUL/SABIHA GOKCEN airport |

**Table E.1:** Arrival and Departure Airports in the small model used to validate the algoritme

# F

# Benefits of a HSR station at the airport

To promote the Air-Rail use the study sugested that it is necessary for airports to have a HSR station. This will stimulate the use of the HSR network. However, what benefits does an HSR station in an airport offer passengers? To understand this, it is important to consider the average time required between arrival and departure. As an airport is often a hub of multiple mobilities, arrival can occur through various options. To understand the influence of an HSR station, a few examples will be discussed below regarding the time it takes to enter and leave an airport.

## F.0.1. Arriving by car

Figure F.1 provides a brief overview of what arriving at an airport by car might entail. At Schiphol and other airports, individuals are advised to arrive three hours before departure when driving. This is due to the often complicated nature of parking, which can be crowded and make finding a spot challenging. Additionally, parking spaces at large airports are frequently spacious but located further from the terminal, resulting in long walking distances for passengers. Upon arriving at the terminal, a standard process begins that all types of passengers must go through. This will not differ for those arriving with different mobility needs. In total arriving by car will approximately take 180 minutes.

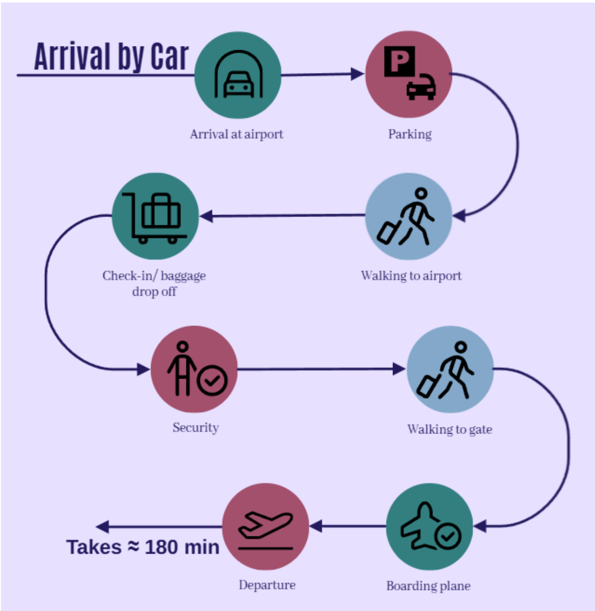


**Figure F.1:** Arriving by car

## F.0.2. Departing without an HSR station

After an aircraft lands at the airport, the passenger has two options: either leave the airport and transfer to another mode of transport or transfer to another aircraft. Switching to another mode of transport includes options such as a bus or taxi. To provide clarity, the high-speed rail (HSR) will also be compared to a car. Additionally, transferring to another flight will be considered, as this study ultimately focuses on two options for the passenger: a transfer between two planes or a transfer to a train.

Figure F.2 shows a simplified representation of the different steps a passenger must go through when arriving at an airport and changing to another mode of transport. The initial steps are the same for all passengers, regardless of whether they transfer to a bus or a car. Note that when a passenger has a transfer between two aircraft, this process differs.

The process begins with leaving the aircraft. Once the passenger has disembarked, they must go through passport control. For passengers arriving from Europe, this will be quicker than for those who need to apply for a visa. However, the difference in processing times is offset by the luggage. This is because the luggage arrives simultaneously and must be unloaded from the aircraft first, which can take some time. Therefore, it will ultimately take all passengers about 40 minutes to exit the airside of the airport.

The moment passengers leave the airside, the process varies for each mobility option. For a passenger using a car, the first step is to head to the parking garage to retrieve the vehicle. According to Schiphol, this walk should take about five minutes (Schiphol Airport (2024)). Once at the car, the passenger simply needs to get in and drive away. This means that when a passenger uses a car, it will take approximately 45 minutes after leaving the plane before they are completely gone.

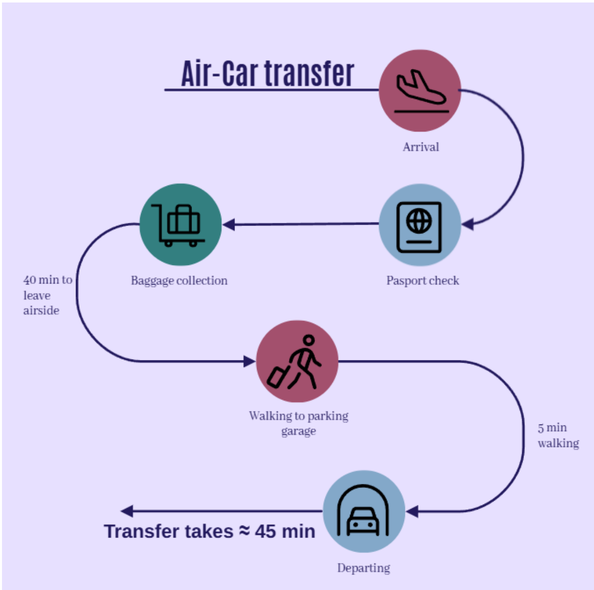


**Figure F.2:** Leaving the airport by car

The moment a passenger transfers between two aircraft, the process differs from when a passenger changes mobility. Figure F.3 illustrates a scenario where a passenger transfers between two flights within the Schengen area. In the figure, two different flows are highlighted; the first is the process the passenger must follow to reach the new gate, which takes only 15 minutes. This changes when an airport is not a hub, as the passenger must leave the airside and check in again. If this occurs, it will cost the passenger at least an extra 60 minutes of transfer time.

When the passenger arrives at the gate, he must wait until the flight departs. This is where the bottleneck in the transfer occurs. The reason the passenger must wait for his next flight is that the luggage is still on the previous aircraft and needs to be moved to the next one, as shown in Figure F.3. This process takes longer than the time required for the passenger to switch between gates. Therefore, a passenger's transfer time depends on the luggage. According to various airports, including Schiphol and Frankfurt, this process takes around 60 minutes. Thus, the time to transfer between two flights is approximately 60 minutes.

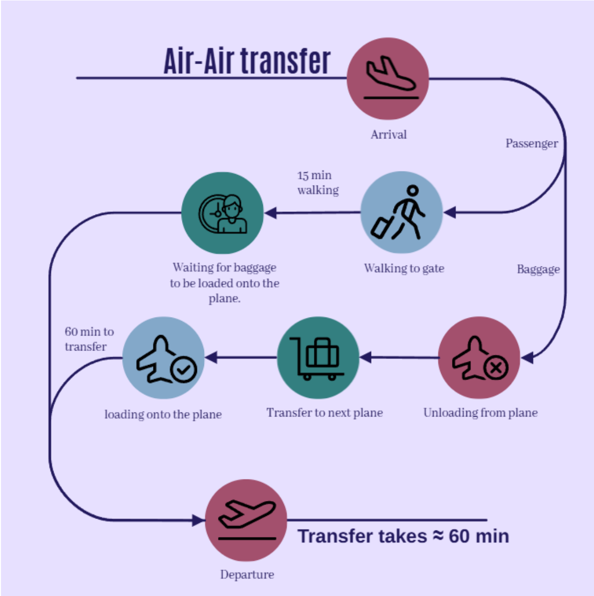


**Figure F.3:** Transfer between two different planes

In this study, in addition to the effect of the ban. The impact of a High-Speed Rail (HSR) station on an airport will also be examined during periods when the airport's ban is in effect. When a ban is in place and a passenger wishes to transfer from an airport to another long-distance transport option, one of the few alternatives to flying is to use the HSR. If an airport lacks an HSR option, the passenger must travel to the station using another mode of transport. The steps a passenger must take in this situation are illustrated in Figure F.4.

To leave the airside, the passenger must follow the same procedures as other systems to switch between different mobility options. Once outside the airport, the passenger will need to find a taxi, which are often parked in front of the airport. This allows the passenger to immediately get into the taxi and head to the train station. The ride will take approximately 15 minutes, though it may be longer or shorter depending on the location of the airport and the station. Upon arrival at the station, the passenger will exit the taxi and enter the station.

Upon arriving at the station, the passenger must wait for the train. This waiting time can vary for each passenger, as they may arrive at different times. Generally, it is expected that the HSR will run once an hour. While this may not be the case everywhere, this research assumes that there will always be an HSR departing from the station every hour, resulting in an average wait of 30 minutes for the train. Overall, it will take about 90 minutes for a passenger to transfer to an HSR when it is not at the station. This can be increased by a longer taxi ride.

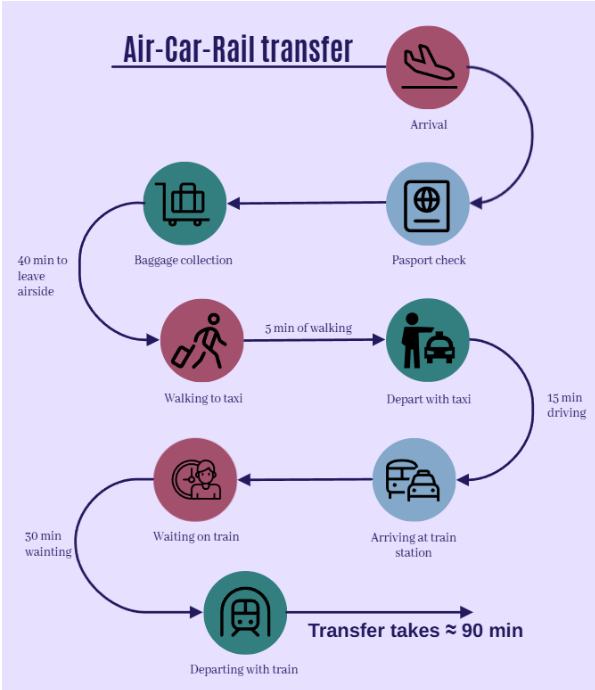


**Figure F.4:** Transfer between air and rail when there isn't a HSR station at the airport

### F.0.3. Airports with HSR stations

When an airport has an HSR station, the transfer and arrival times of passengers differ from those of arriving by car. To provide a clearer picture, two scenarios will be considered. The first is a passenger arriving by train at the airport, and the second is a transfer where a passenger connects to a HSR train at the airport station.

To begin, the process of arriving at an airport via train will be examined. The process a passenger must go through is shown in Figure F.5. In comparison to the car depicted in Figure F.1, the first point to note is that the process starting from check-in is the same, providing little advantage or disadvantage for the passenger. What significantly affects travel time is the absence of parking time for train passengers. This greatly reduces the time needed to enter the airport. Additionally, the train station is often located below the airport, which further contributes to the speed of arriving by train compared to by car. According to Schiphol's advice, it is noteworthy that they recommend passengers arriving by train only need to be present two hours in advance, while those arriving by car are advised to arrive three hours in advance.

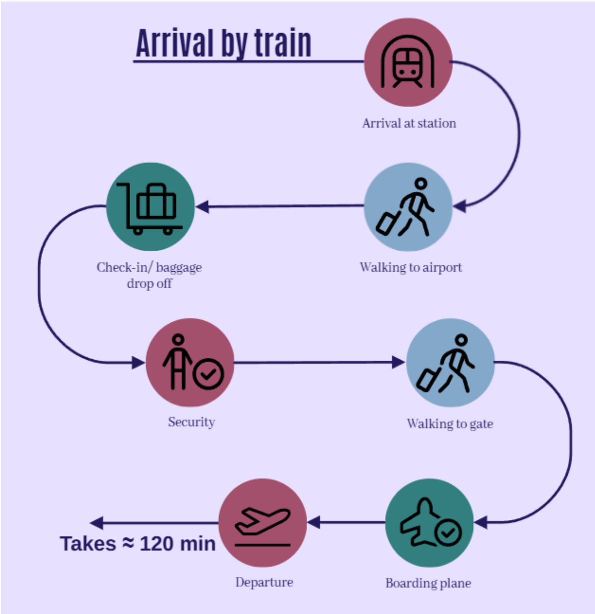


**Figure F.5:** Arriving by train

When a passenger wants to transfer from an aircraft to the HSR, there are two options. The first option, where an airport does not own an HSR station, is illustrated in Figure F.4. If an airport does own an HSR station, it will have a different impact on the passenger. Figure F.6 provides a brief overview of this scenario.

The moment an airport owns an HSR station, it also impacts passenger transfers. In the initial phase of the transfer, nothing will actually change. Passengers must still leave the airport's airside first, which takes about 40 minutes. Once they have exited airside, they can begin walking towards the station. The station is often located beneath the airport itself and is easily accessible from the terminal. According to Schiphol's site(Schiphol Airport (2024)), this walk will take about 5 minutes. Upon reaching the station, passengers should account for waiting time. As noted earlier, this study assumes that one HSR train runs every hour, resulting in an average waiting time of 30 minutes.

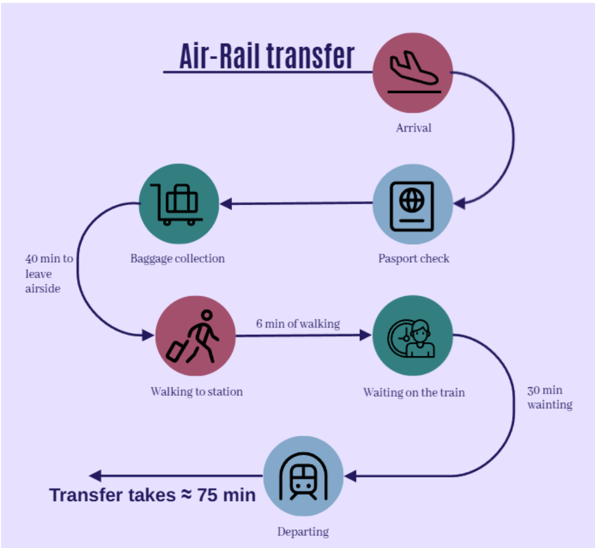


**Figure F.6:** Transfer between air and rail when there is a HSR station at the airport

In the end, the passenger always has to wait at the station for the train. The key difference lies primarily in the travel time between the airport and the station. Additionally, a taxi ride between two long-distance locations can cause significant stress for the passenger. Therefore, it can be expected that a passenger will be less inclined to use the HSR if it is not available at the station.

Within this study, passengers also have the option to transfer to a new flight. When comparing this type of transfer with an Air-Rail transfer, it is evident that the Air-Air transfer is faster overall. This can be attributed to the relatively high average waiting time on the HSR. If a passenger plans their journey more effectively, this waiting time may decrease. However, the results still indicate that passengers are more likely to choose a transfer to a new flight than to an HSR.

# G

# Data of the different cities used in this stuy

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Tirana | TIRA | 41.3268733 | 19.8187913 | T | 895,160 | Albania | AL | EU |
| Linz | LINZ | 48.3059078 | 14.286198 | L | 801,085 | Austria | AT | EU |
| Vienna | VIEN | 48.2083537 | 16.3725042 | V | 2,853,903 | Austria | AT | EU |
| Minsk | MINS | 53.902334 | 27.5618791 | M | 2,645,500 | Belarus | BY | EU |
| Antwerpen | ANTW | 51.2211097 | 4.3997081 | A | 1,053,033 | Belgium | BE | EU |
| Brussels | BRUS | 50.8465573 | 4.351697 | B | 2,548,941 | Belgium | BE | EU |
| Gent | GENT | 51.0538286 | 3.7250121 | G | 646,068 | Belgium | BE | EU |
| Liege | LIEG | 50.6451381 | 5.5734203 | L | 708,125 | Belgium | BE | EU |
| Sarajevo | SARA | 43.8519774 | 18.3866868 | S | 555,210 | Bosnia and Herzegovina | BA | EU |
| Plovdiv | PLOV | 42.1418541 | 24.7499297 | P | 668,334 | Bulgaria | BG | EU |
| Sofia | SOFI | 42.6978634 | 23.3221789 | S | 1,678,041 | Bulgaria | BG | EU |
| Zagreb | ZAGR | 45.813177 | 15.977048 | Z | 1,240,433 | Croatia | HR | EU |
| Brno | BRNO | 49.1922443 | 16.6113382 | B | 1,187,667 | Czech Republic | CZ | EU |
| Ostrava | OSTR | 49.8349139 | 18.2820084 | O | 1,203,299 | Czech Republic | CZ | EU |
| Prague | PRAG | 50.0874654 | 14.4212535 | P | 2,677,964 | Czech Republic | CZ | EU |
| Arhus | ARHU | 56.1496278 | 10.2134046 | A | 890,567 | Denmark | DK | EU |
| Copenhagen | COPE | 55.6867243 | 12.5700724 | C | 2,045,259 | Denmark | DK | EU |
| Tallinn | TALL | 59.4372155 | 24.7453688 | T | 599,478 | Estonia | EE | EU |
| Helsinki | HELS | 60.1674098 | 24.9425769 | H | 1,671,024 | Finland | FI | EU |
| Tampere | TAMP | 61.4980214 | 23.7603118 | T | 515,095 | Finland | FI | EU |
| Bordeaux | BORD | 44.841225 | -0.5800364 | B | 1,617,189 | France | FR | EU |
| Grenoble | GREN | 45.1875602 | 5.7357819 | G | 1,263,351 | France | FR | EU |
| Lille | LILL | 50.6365654 | 3.0635282 | L | 2,594,456 | France | FR | EU |
| Lyon | LYON | 45.7578137 | 4.8320114 | L | 1,865,534 | France | FR | EU |
| Marseille | MARS | 43.2961743 | 5.3699525 | M | 3,100,329 | France | FR | EU |
| Montpellier | MONT | 43.6112422 | 3.8767337 | M | 1,166,070 | France | FR | EU |
| Nantes | NANT | 47.2186371 | -1.5541362 | N | 1,423,365 | France | FR | EU |
| Nice | NICE | 43.7009358 | 7.2683912 | N | 1,080,815 | France | FR | EU |
| Paris | PARI | 48.8566969 | 2.3514616 | P | 12,244,807 | France | FR | EU |
| Rennes | RENN | 48.1113387 | -1.6800198 | R | 1,074,841 | France | FR | EU |
| Rouen | ROUE | 49.4404591 | 1.0939658 | R | 1,247,452 | France | FR | EU |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Strasbourg | STRA | 48.584614 | 7.7507127 | S | 1,130,370 | France | FR | EU |
| Toulon | TOUN | 43.1257311 | 5.9304919 | T | 579,000 | France | FR | EU |
| Toulouse | TOUS | 43.6044622 | 1.4442469 | T | 1,388,447 | France | FR | EU |
| Aachen | AACH | 50.776351 | 6.083862 | A | 555,465 | Germany | DE | EU |
| Berlin | BERL | 52.5170365 | 13.3888599 | B | 5,303,846 | Germany | DE | EU |
| Bremen | BREM | 53.0758196 | 8.8071646 | B | 1,277,609 | Germany | DE | EU |
| Dresden | DRES | 51.0493286 | 13.7381437 | D | 1,343,305 | Germany | DE | EU |
| Dusseldorf | DUSS | 51.2254018 | 6.7763137 | D | 1,555,985 | Germany | DE | EU |
| Frankfurt Am Main | FRAN | 50.1106444 | 8.6820917 | F | 2,356,035 | Germany | DE | EU |
| Hamburg | HAMB | 53.543766 | 10.009915 | H | 3,327,940 | Germany | DE | EU |
| Hannover | HANN | 52.379097 | 9.742982 | H | 1,315,405 | Germany | DE | EU |
| Karlsruhe | KARL | 49.0068725 | 8.403475 | K | 757,324 | Germany | DE | EU |
| Kiel | KIEL | 54.3227085 | 10.135555 | K | 648,970 | Germany | DE | EU |
| Cologne | COLO | 50.938361 | 6.959974 | C | 2,003,046 | Germany | DE | EU |
| Leipzig | LEIP | 51.3406321 | 12.3747329 | L | 1,043,293 | Germany | DE | EU |
| Mannheim | MANN | 49.489591 | 8.467236 | M | 1,189,073 | Germany | DE | EU |
| Munich | MUNI | 48.1371079 | 11.5753822 | M | 2,908,664 | Germany | DE | EU |
| Ruhrgebiet (Essen) | RUHR | 51.4118742 | 7.025698 | R | 5,111,530 | Germany | DE | EU |
| Saarbrucken | SAAR | 49.234362 | 6.996379 | S | 799,746 | Germany | DE | EU |
| Stuttgart | STUT | 48.7784485 | 9.1800132 | S | 2,787,724 | Germany | DE | EU |
| Athens | ATHE | 37.9839412 | 23.7283052 | A | 3,561,750 | Greece | EL | EU |
| Thessaloniki | THES | 40.6403167 | 22.9352716 | T | 1,104,690 | Greece | EL | EU |
| Budapest | BUDA | 47.4983815 | 19.0404707 | B | 3,031,160 | Hungary | HU | EU |
| Dublin | DUBL | 53.3497645 | -6.2602732 | D | 2,107,749 | Ireland | IE | EU |
| Bari | BARI | 41.1257843 | 16.8620293 | B | 1,251,994 | Italy | IT | EU |
| Bologna | BOLO | 44.4936714 | 11.3430347 | B | 1,014,619 | Italy | IT | EU |
| Brescia | BRES | 45.539841 | 10.22296 | B | 1,265,954 | Italy | IT | EU |
| Catania | CATA | 37.5022355 | 15.08738 | C | 1,107,702 | Italy | IT | EU |
| Florence | FLOR | 43.7698712 | 11.2555757 | F | 1,011,349 | Italy | IT | EU |
| Genoa | GENO | 44.40726 | 8.9338624 | G | 841,180 | Italy | IT | EU |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Milano | MILA | 45.4668 | 9.1905 | M | 4,354,448 | Italy | IT | EU |
| Napoli | NAPO | 40.8359336 | 14.2487826 | N | 3,084,890 | Italy | IT | EU |
| Palermo | PALE | 38.1112268 | 13.3524434 | P | 1,252,588 | Italy | IT | EU |
| Rome | ROME | 41.8933203 | 12.4829321 | R | 4,342,212 | Italy | IT | EU |
| Turin | TURI | 45.0677551 | 7.6824892 | T | 2,259,523 | Italy | IT | EU |
| Venice | VENI | 45.43876 | 12.327145 | V | 853,338 | Italy | IT | EU |
| Verona | VERO | 45.4384958 | 10.9924122 | V | 926,497 | Italy | IT | EU |
| Pristina | PRIS | 42.6638771 | 21.1640849 | P | 493,058 | Kosovo | XK | EU |
| Riga | RIGA | 56.9493977 | 24.1051846 | R | 1,003,203 | Latvia | LV | EU |
| Vilnius | VILN | 54.68199155 | 25.25625728 | V | 810,538 | Latvia | LV | EU |
| Luxembourg | LUXE | 49.8158683 | 6.1296751 | L | 613,894 | Luxembourg | LU | EU |
| Skopje | SKOP | 41.9960924 | 21.4316495 | S | 630,817 | Republic of North Macedonia | MK | EU |
| Chisinau | CHIS | 47.0244707 | 28.8322534 | C | 2,863,700 | Moldova | MD | EU |
| Podgorica | PODG | 42.4415238 | 19.2621081 | P | 201,631 | Montenegro | ME | EU |
| Bergen | BERG | 60.3943055 | 5.3259192 | B | 1,000,149 | Norway | NO | EU |
| Oslo | OSLO | 59.9133301 | 10.7389701 | O | 1,305,122 | Norway | NO | EU |
| Gdansk | GDAN | 54.347629 | 18.6452324 | G | 3,199,843 | Poland | PO | EU |
| Katowice | KATO | 50.2598987 | 19.0215852 | K | 823,655 | Poland | PO | EU |
| Krakow | KRAK | 50.0619474 | 19.9368564 | K | 1,491,811 | Poland | PO | EU |
| Lodz | LODZ | 51.7687323 | 19.4569911 | L | 1,070,544 | Poland | PO | EU |
| Lublin | LUBL | 51.2181945 | 22.55467757 | L | 709,993 | Poland | PO | EU |
| Poznan | POZN | 52.40063215 | 16.91978694 | P | 1,194,454 | Poland | PO | EU |
| Rzeszow | RZES | 50.00715125 | 22.00991153 | R | 631,399 | Poland | PO | EU |
| Warsaw | WARS | 52.2319581 | 21.0067249 | W | 3,053,104 | Poland | PO | EU |
| Wroclaw | WROC | 51.1263106 | 16.97819633 | W | 638,659 | Poland | PO | EU |
| Lisbon | LISB | 38.7077507 | -9.1365919 | L | 2,846,332 | Portugal | PT | EU |
| Porto | PORT | 41.1494512 | -8.6107884 | P | 1,722,374 | Portugal | PT | EU |
| Bucharest | BUCH | 44.4361414 | 26.1027202 | B | 2,315,173 | Romania | RO | EU |
| Cluj-Napoca | CLUJ | 46.769379 | 23.5899542 | C | 706,905 | Romania | RO | EU |
| Iasi | IASI | 47.1615341 | 27.5836142 | I | 793,559 | Romania | RO | EU |
| Kaliningrad | KALI | 54.710128 | 20.5105838 | K | 482,443 | Russia | RU | EU |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Moscow | MOSC | 55.7504461 | 37.6174943 | M | 12,432,531 | Russia | RU | EU |
| Machatsjkala | MACH | 42.9728344 | 47.4936809 | M | 577,990 | Russia | RU | ASI |
| Kazan | KAZA | 55.7887 | 49.1221 | K | 1,251,969 | Russia | RU | ASI |
| Sotsji | SOTS | 43.59917 | 39.72569 | S | 343,285 | Russia | RU | ASI |
| St. Petersburg | STPE | 59.93848 | 30.312481 | S | 5,383,890 | Russia | RU | EU |
| Belgrade | BELG | 44.8178131 | 20.4568974 | B | 1,691,919 | Serbia | RS | EU |
| Bratislava | BRAT | 48.1516988 | 17.1093063 | B | 659,598 | Slovakia | SK | EU |
| Kosice | KOSI | 48.7172272 | 21.2496774 | K | 800,414 | Slovakia | SK | EU |
| Ljubljana | LJUB | 46.0499803 | 14.5068602 | L | 549,171 | Slovenia | SI | EU |
| Barcelona | BARC | 41.3828939 | 2.1774322 | B | 5,575,204 | Spain | ES | EU |
| Bilbao | BILB | 43.2630051 | -2.9349915 | B | 1,137,191 | Spain | ES | EU |
| Madrid | MADR | 40.4167047 | -3.7035825 | M | 6,641,649 | Spain | ES | EU |
| Sevilla | SEVI | 37.3886303 | -5.9953403 | S | 1,949,640 | Spain | ES | EU |
| Valencia | VALE | 39.466667 | -0.375 | V | 2,540,588 | Spain | ES | EU |
| Zaragoza | ZARA | 41.6521342 | -0.8809428 | Z | 968,049 | Spain | ES | EU |
| Gothenburg | GOTH | 57.7072326 | 11.9670171 | G | 1,709,814 | Sweden | SE | EU |
| Stockholm | STOC | 59.3251172 | 18.0710935 | S | 2,344,124 | Sweden | SE | EU |
| Basel | BASE | 47.5581077 | 7.5878261 | B | 711,537 | Switzerland | CH | EU |
| Geneva | GENE | 46.2017559 | 6.1466014 | G | 499,480 | Switzerland | CH | EU |
| Zurich | ZURI | 47.3723941 | 8.5423328 | Z | 1,520,968 | Switzerland | CH | EU |
| Amsterdam | AMST | 52.3745403 | 4.897975506 | A | 3,269,905 | Netherlands | NL | EU |
| Eindhoven | EIND | 51.44855695 | 5.450122522 | E | 773,203 | Netherlands | NL | EU |
| Groningen | GRON | 53.2190652 | 6.5680077 | G | 437,187 | Netherlands | NL | EU |
| Rotterdam | ROTT | 51.9228958 | 4.4631727 | R | 1,846,933 | Netherlands | NL | EU |
| Utrecht | UTRE | 52.0949753 | 5.109708 | U | 1,306,912 | Netherlands | NL | EU |
| Ankara | ANKA | 39.9207774 | 32.854067 | A | 5,503,985 | Turkey | TR | ASI |
| Istanbul | ISTA | 41.0096334 | 28.9651646 | I | 15,067,724 | Turkey | TR | ASI |
| Kiev | KIEV | 50.4500336 | 30.5241361 | K | 2,950,819 | Ukraine | UA | EU |
| Birmingham | BIRM | 52.4796992 | -1.9026911 | B | 1,148,862 | United Kingdom | UK | EU |
| Edinburgh | EDIN | 55.9533456 | -3.1883749 | E | 901,455 | United Kingdom | UK | EU |
| Glasgow | GLAS | 55.8609825 | -4.2488787 | G | 1,861,315 | United Kingdom | UK | EU |
| Leeds | LEED | 53.7974185 | -1.5437941 | L | 1,750,276 | United Kingdom | UK | EU |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Liverpool | LIVE | 53.407154 | -2.991665 | L | 1,784,475 | United Kingdom | UK | EU |
| London | LOND | 51.5073219 | -0.1276474 | L | 14,372,596 | United Kingdom | UK | EU |
| Manchester | MANC | 53.4794892 | -2.2451148 | M | 3,712,997 | United Kingdom | UK | EU |
| Newcastle Upon Tyne | NEWC | 54.9738474 | -1.6131572 | N | 1,177,704 | United Kingdom | UK | EU |
| Abu Dhabi | ABUD | 24.466667 | 54.366669 | A | 1,512,000 | United Arab Emirates | AE | MiE |
| Dubai | DUBA | 25.26667 | 55.31667 | D | 3,638,000 | United Arab Emirates | AE | MiE |
| Singapore | SING | 1.29027 | 103.851959 | S | 5,918,000 | Singapore | SG | ASI |
| Castleisland | CAST | 52.2353234 | -9.468298 | C | 2,536 | Ireland | IE | EU |
| Belfast | BELF | 54.607868 | -5.926437 | B | 348,005 | United Kingdom | UK | EU |
| Bristol | BRIS | 51.454514 | -2.58791 | B | 16,807 | United Kingdom | UK | EU |
| Trondheim | TRON | 63.446827 | 10.421906 | T | 212,660 | Norway | NO | EU |
| Umea | UMEA | 63.825848 | 20.263035 | U | 130000 | Sweden | SE | EU |
| Luleå | LULE | 65.584816 | 22.156704 | L | 43,574 | Sweden | SE | EU |
| Oulu | OULU | 65.021545 | 25.469885 | O | 207,327 | Finland | FI | EU |
| Reykjavik | REYK | 64.051306 | -21.99328 | R | 139,875 | Iceland | IS | EU |
| İzmir | IZMI | 38.423733 | 27.142826 | T | 3,209,179 | Turkey | TR | ASI |
| Eskişehir | ESKI | 39.766193 | 30.526714 | O | 797,708 | Turkey | TR | ASI |
| Adana | ADAN | 37.00 | 35.321335 | A | 2,263,000 | Turkey | TR | ASI |
| Dalaman | DALA | 36.8212265 | 28.92068869 | D | 16,162 | Turkey | TR | ASI |
| Antalya | ANTA | 36.9009641 | 30.6954846 | A | 2,619,832 | Turkey | TR | ASI |
| Konya | KONY | 37.87135 | 32.48464 | K | 2,320,000 | Turkey | TR | ASI |
| Kayseri | KAYS | 38.73222 | 35.48528 | K | 1,442,000 | Turkey | TR | ASI |
| Sivas | SIVA | 39.750545 | 37.0150217 | S | 381,325 | Turkey | TR | ASI |
| Gaziantep | GAZI | 37.066666 | 37.383331 | G | 2,130,000 | Turkey | TR | ASI |
| Aqtau | AQTA | 43.64806 | 51.17222 | A | 276,792 | Kazachstan | KZ | ASI |
| Astana | ASTA | 51.169392 | 71.449074 | A | 1,550,000 | Kazachstan | KZ | ASI |
| Alma-Ata | ALMA | 43.238949 | 76.889709 | A | 2,195,000 | Kazachstan | KZ | ASI |
| Jerevan | JERE | 40.1772 | 44.50349 | T | 1,098,000 | Armenië | AM | ASI |
| Baku | BAKU | 40.409264 | 49.867092 | B | 2,675,000 | Azerbeidzjan | AZ | ASI |
| Tibilisi | TIBI | 41.69751 | 44.8271 | T | 1,259,000 | Georgië | GE | ASI |
| Koetaisi | KOET | 42.26791 | 42.69459 | K | 125,589 | Georgië | GE | ASI |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Batoemi | BATO | 41.64288 | 41.63392 | B | 183,181 | Georgië | GE | ASI |
| Tasjkent | TASJ | 41.34557 | 69.284599 | T | 3,095,498 | Uzbekistan | UZ | ASI |
| Samarkand | SAMA | 39.652451 | 66.970139 | S | 950,000 | Uzbekistan | UZ | ASI |
| Bisjkek | BISJ | 42.882004 | 74.582748 | B | 1,138,000 | Kyrgyzstan | KG | ASI |
| Lahore | LAHO | 31.582045 | 74.329376 | L | 11,126,285 | Pakistan | PK | ASI |
| Islamabad | ISLA | 33.738045 | 73.084488 | I | 2,363,863 | Pakistan | PK | ASI |
| Teheran | TEHE | 35.715298 | 51.404343 | T | 15,800,000 | Iran | IR | MiE |
| Koeweit-stad | KOEW | 29.31166 | 47.481766 | K | 2,380,000 | Koeweit | KW | MiE |
| Nicosia | NICO | 35.185566 | 33.382275 | N | 276,410 | Cyprus | CY | MiE |
| Beiroet | BEIR | 33.88894 | 35.49442 | B | 2,060,363 | Libanon | LB | MiE |
| Tel Aviv | TELA | 32.0853 | 34.78057 | T | 4,156,900 | Israel | IL | MiE |
| Amman | AMMA | 31.963158 | 35.930359 | A | 4,300,000 | Jordanië | JO | MiE |
| Djedda | DJED | 21.54238 | 39.19797 | D | 3,713,000 | Saudi Arabia | SA | MiE |
| Riyad | RIYA | 24.68773 | 46.72185 | R | 7,009,000 | Saudi Arabia | SA | MiE |
| Manama | MANA | 26.201 | 50.606998 | M | 297,502 | Bahrein | BH | MiE |
| Doha | DOHA | 25.286106 | 51.534817 | D | 796,947 | Qatar | QA | MiE |
| Masqat | MASQ | 23.592306 | 58.28616 | M | 1,310,181 | Oman | OM | MiE |
| New Delhi | NEWD | 28.6448 | 77.216721 | N | 27,280,000 | India | IN | ASI |
| Mumbai | MUMB | 18.9387711 | 72.8353355 | M | 19,980,000 | India | IN | ASI |
| Bangaluru | BANG | 12.971599 | 77.594566 | B | 8,425,970 | India | IN | ASI |
| Chennai | CHEN | 13.067439 | 80.237617 | C | 8,696,010 | India | IN | ASI |
| Malé | MALE | 4.17521 | 73.399658 | M | 104,000 | Maladiven | MV | ASI |
| Beijing | BEIJ | 39.916668 | 116.383331 | B | 22,366,547 | China | CN | ASI |
| Shanghai | SHAN | 31.224361 | 121.46917 | S | 40,000,000 | China | CN | ASI |
| Xiamen | XIAM | 24.47979 | 118.08187 | X | 13,223,681 | China | CN | ASI |
| Guangzhou | GUAN | 23.128994 | 113.25325 | G | 68,500,000 | China | CN | ASI |
| Hong Kong | HONG | 22.302711 | 114.177216 | H | 7,536,000 | Hong Kong | HK | ASI |
| Hanoi | HANO | 21.028511 | 105.804817 | H | 8,587,000 | Vietnam | VN | ASI |
| Ho Chi Minh | HOCHI | 10.82302 | 106.62965 | H | 8,900,000 | Vietnam | VN | ASI |
| Bangkok | BANGK | 13.736717 | 100.523186 | B | 17,400,000 | Thailand | TH | ASI |
| Phuket | PHUK | 7.878978 | 98.398392 | P | 250,474 | Thailand | TH | ASI |
| Kuala lumpur | KUAL | 3.140853 | 101.693207 | K | 7,564,000 | Maleisië | MY | ASI |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Denpasar | DENP | -8.65 | 115.216667 | D | 1,785,800 | Indonesië | ID | ASI |
| New Taipei | NEWT | 25.105497 | 121.597366 | N | 4,004,387 | Taiwan | TW | ASI |
| Seoul | SEOU | 37.5326 | 127.024612 | S | 9,411,000 | Zuid-korea | KR | ASI |
| Osaka | OSAK | 34.672314 | 135.484802 | O | 2,750,812 | Japan | JP | ASI |
| Tokyo | TOKY | 35.62832 | 139.839478 | T | 14,200,331 | Japan | JP | ASI |
| Port Louis | PORTL | -20.16194 | 57.49889 | P | 120,376 | Mauritius | MU | AFR |
| Saint-Dennis | DENN | -20.878901 | 55.448101 | S | 156,149 | Réunion | RE | AFR |
| Antananarivo | ANTAN | -18.9137 | 47.5361 | A | 2,200,000 | Madagaskar | MG | AFR |
| Pamandzi | PAMA | -12.809645 | 45.130741 | P | 11,442 | Mayotte | YT | AFR |
| Maputo | MAPU | -25.953724 | 32.588711 | M | 1,766,823 | Mozambique | MZ | AFR |
| Johannesburg | JOHA | -26.195246 | 28.034088 | J | 4,803,262 | Zuid-afrika | ZA | AFR |
| Cape Town | CAPE | -33.918861 | 18.4233 | C | 4,773,000 | Zuid-afrika | ZA | AFR |
| Windhoek | WIND | -22.55941 | 17.08323 | W | 322,500 | Namibië | NA | AFR |
| Luanda | LUAN | -8.838333 | 13.234444 | L | 9,080,000 | Angola | AO | AFR |
| Brazzaville | BRAZ | -4.267778 | 15.291944 | B | 2,146,000 | Congo | CG | AFR |
| Libreville | LIBRE | 0.3901 | 9.4544 | L | 703,939 | Gabon | GA | AFR |
| Sao Tome | SAOT | 0.255436 | 6.602781 | S | 231,856 | Sao Tome en Principe | ST | AFR |
| Douala | DOUA | 4.061536 | 9.786072 | D | 1,906,962 | Kameroen | CM | AFR |
| Yaoundé | YAOU | 3.844119 | 11.501346 | Y | 1,817,524 | Kameroen | CM | AFR |
| Abuja | ABUJ | 9.072264 | 7.491302 | A | 6,000,000 | Nigeria | NG | AFR |
| Lagos | LAGO | 6.4550575 | 3.3941795 | L | 14,860,000 | Nigeria | NG | AFR |
| Porto-Novo | PORTN | 6.49646 | 2.60359 | P | 264,320 | Benin | BJ | AFR |
| Lomé | LOMÉ | 6.136629 | 1.222186 | L | 1,500,000 | Togo | TG | AFR |
| Accra | ACCR | 5.614818 | -0.205874 | A | 5,455,692 | Ghana | GH | AFR |
| Abidjan | ABID | 5.345317 | -4.024429 | A | 4,707,000 | Ivoorkust | CI | AFR |
| Conakry | CONA | 9.509167 | -13.712222 | C | 1,826,019 | Guinee | GN | AFR |
| Bamako | BAMA | 12.635898 | -7.971547 | B | 1,810,366 | Mali | ML | AFR |
| Dakar | DAKA | 14.716677 | -17.467686 | D | 3,896,564 | Senegal | SN | AFR |
| Espargos | ESPAR | 16.7560469 | -22.9386472 | E | 24,500 | Kaapverdië | CV | AFR |
| Praia | PRAI | 14.93152 | -23.51254 | P | 142,009 | Kaapverdië | CV | AFR |
| Mindelo | MIND | 16.89014 | -24.98042 | M | 70,468 | Kaapverdië | CV | AFR |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Santa Cruz de La Palma | CRUZP | 28.6818901 | -17.7663354 | S | 15,711 | Spain | ES | AFR |
| Santa Cruz de Tenerife | SANT | 28.46824 | -16.25462 | S | 208,103 | Spain | ES | AFR |
| Las Palmas de Gran Canaria | LASP | 28.15 | -15.416667 | L | 378,998 | Spain | ES | AFR |
| Peurto del Rosario | PEUR | 28.5004 | -13.8627 | P | 38,126 | Spain | ES | AFR |
| Arrecife | ARRE | 28.96302 | -13.54769 | A | 58,537 | Spain | ES | AFR |
| Funchal | FUNC | 32.63333 | -16.9 | F | 105,701 | Portugal | PT | AFR |
| Vila Baleira | VILAB | 33.0667 | -16.333 | V | 5,158 | Portugal | PT | AFR |
| Ponta Delgada | PONTA | 37.742828 | -25.680588 | P | 64,497 | Portugal | PT | AFR |
| Angra do Heroísme | ANGRA | 38.6558 | -27.2153 | A | 21,000 | Portugal | PT | AFR |
| Horta | HORTA | 38.53737 | -28.62615 | H | 15,343 | Portugal | PT | AFR |
| Agadir | AGAD | 30.427755 | -9.598107 | A | 504,768 | Marocco | MA | AFR |
| Marrakech | MARR | 31.628674 | -7.992047 | M | 1,014,813 | Marocco | MA | AFR |
| Casablanca | CASAB | 33.589886 | -7.603869 | C | 3,218,036 | Marocco | MA | AFR |
| Rabat | RABAT | 34.020882 | -6.84165 | R | 1,932,000 | Marocco | MA | AFR |
| Tanger | TANG | 35.7594651 | -5.8339543 | T | 1,314,000 | Marocco | MA | AFR |
| Fes | FES | 34.03715 | -4.9998 | F | 1,182,963 | Marocco | MA | AFR |
| Nador | NADO | 35.16813 | -2.93352 | N | 158,202 | Marocco | MA | AFR |
| Oran | ORAN | 35.69111 | -0.64167 | O | 1,570,000 | Algerije | DZ | AFR |
| Alger | ALGER | 36.737232 | 3.086472 | A | 2,481,788 | Algerije | DZ | AFR |
| Constantine | CONST | 36.365 | 6.6147 | C | 462,187 | Algerije | DZ | AFR |
| Tunis | TUNIS | 36.806389 | 10.181667 | T | 599,368 | Tunesië | TN | AFR |
| Sousse | SOUS | 35.82143 | 10.634422 | S | 314,071 | Tunesië | TN | AFR |
| Houmt Souk | HOUMT | 33.87576 | 10.85745 | H | 44,555 | Tunesië | TN | AFR |
| Tripoli | TRIPO | 32.885353 | 13.180161 | T | 2,200,000 | Libië | LY | AFR |
| Caïro | CAIRO | 30.0333333 | 31.233334 | C | 22,183,000 | Egypte | EG | AFR |
| Hurghada | HURG | 27.25738 | 33.81291 | H | 160,746 | Egypte | EG | AFR |
| Sharm-el-Sheikh | SHARM | 27.915817 | 34.329948 | S | 13,561 | Egypte | EG | AFR |
| Luxor | LUXOR | 25.687243 | 32.639637 | L | 430,000 | Egypte | EG | AFR |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Addis Abeba | ADDIS | 9.005401 | 38.763611 | A | 5,704,000 | Ethiopia | ET | AFR |
| Kampala | KAMP | 0.347596 | 32.58252 | K | 6,709,900 | Uganda | UG | AFR |
| Nairobi | NAIRO | -1.286389 | 36.817223 | N | 3,363,000 | Kenya | KE | AFR |
| Arusha | ARUSH | -3.386925 | 36.682995 | A | 270,485 | Tanzania | TZ | AFR |
| Mombasa | MOMBA | -4.04374 | 39.658871 | M | 1,208,333 | Kenya | KE | AFR |
| Buenos-Aires | BUENOS | -34.603722 | -58.381592 | B | 15,370,000 | Argentinië | AR | ZoA |
| Córdoba | CORDO | -31.416668 | -64.183334 | C | 322,327 | Argentinië | AR | ZoA |
| Santiago | SANTIA | -33.447487 | -70.673676 | S | 5,220,161 | Chile | CL | ZoA |
| Lima | LIMA | -12.046374 | -77.042793 | L | 11,283,787 | Peru | PE | ZoA |
| Montevideo | MONTE | -34.901112 | -56.164532 | M | 1,384,000 | Uruguay | UY | ZoA |
| Porto Algre | ALEGRE | -30.033056 | -51.23 | P | 1,332,570 | Brazilië | BR | ZoA |
| Sao Paulo | SAUP | -23.5337733 | -46.62529 | S | 11,450,000 | Brazilië | BR | ZoA |
| Rio de Janeiro | RIO | -22.908333 | -43.196388 | R | 6,211,000 | Brazilië | BR | ZoA |
| Belo Horizonte | BELO | -19.912998 | -43.940933 | B | 6,006,887 | Brazilië | BR | ZoA |
| Brasilia | BRASI | -15.793889 | -47.882779 | B | 2,817,000 | Brazilië | BR | ZoA |
| Salvador | SALVA | -12.974722 | -38.476665 | S | 6,365,000 | Brazilië | BR | ZoA |
| Joao Pessoa | JOAO | -7.115 | -34.86306 | J | 1,290,223 | Brazilië | BR | ZoA |
| Natal | NATAL | -5.812757 | -35.255127 | N | 751,300 | Brazilië | BR | ZoA |
| Fortaleza | FORTA | -3.731862 | -38.526669 | F | 2,429,000 | Brazilië | BR | ZoA |
| Santa Cruz | SANTA | -18.418 | -65.345 | S | 2,424,120 | Bolivia | BO | ZoA |
| Oranjestad | ORANJE | 12.510052 | -70.009354 | O | 28,294 | Aruba | AW | ZoA |
| Willemstad | WILLEM | 12.1084 | -68.93354 | W | 101,711 | Curacau | AN | ZoA |
| Kralendijk | KRALEN | 12.1471741 | -68.2740783 | K | 19,011 | Bonaire | AN | ZoA |
| Guayaquil | GUAY | -2.203816 | -79.897453 | G | 2,650,000 | Ecuador | EC | ZoA |
| Quito | QUITO | -0.180653 | -78.467834 | Q | 1,763,000 | Ecuador | EC | ZoA |
| Cali | CALI | 3.420556 | -76.522224 | S | 2,234,000 | Colombia | CO | ZoA |
| Medellin | MEDEL | 6.230833 | -75.590553 | M | 2,400,000 | Colombia | CO | ZoA |
| Bogota | BOGO | 4.624335 | -74.063644 | B | 7,907,000 | Colombia | CO | ZoA |
| Paramaribo | PARA | 5.839398 | -55.199089 | P | 240,924 | Suriname | SR | ZoA |
| Caracas | CARAC | 10.5 | -66.916664 | C | 3,242,000 | Venezuela | VE | ZoA |
| Fort-de-France | FORTF | 14.60892 | -61.07334 | F | 75,165 | France | FR | ZoA |
| Pointe-a-pitre | POINTE | 16.2413 | -61.5361 | P | 14,855 | France | FR | ZoA |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Philipsburg | PHILIP | 18.026 | -63.04582 | P | 2,710 | Sint-maarten | MF | ZoA |
| San Juan | SANJ | 18.466333 | -66.105721 | S | 334,776 | Puerto Rico | PR | ZoA |
| Santo Domingo | SANTO | 18.483402 | -69.929611 | S | 1,029,000 | Dominicaanse Re-publiek | DO | ZoA |
| Havana | HAVAN | 23.113592 | -82.366592 | H | 2,129,561 | Cuba | CU | ZoA |
| Panama-stad | PANAM | 8.983333 | -79.51667 | P | 1,272,672 | Panama | PA | NoA |
| San José | SANJO | 9.934739 | -84.087502 | S | 2,000,468 | Costa Rica | CR | NoA |
| San Salvador | SANS | 13.6929403 | -89.2181911 | S | 2,177,432 | El salvador | SV | NoA |
| Guatemala-stad | GUAT | 14.628434 | -90.522713 | G | 1,222,000 | Guatemala | GT | NoA |
| Cancún | CANC | 21.17429 | -86.84656 | C | 888,797 | Mexico | MX | NoA |
| Mexico-stad | MEXI | 19.4326077 | -99.133208 | M | 9,209,944 | Mexico | MX | NoA |
| Guadalajara | GUAD | 20.659698 | -103.349609 | G | 1,380,621 | Mexico | MX | NoA |
| New York | NYC | 40.7127281 | -74.0060152 | N | 8,258,000 | USA | US | NoA |
| Los Angeles | LOSA | 34.052235 | -118.243683 | L | 3,821,000 | USA | US | NoA |
| San Diego | SAND | 32.715736 | -117.161087 | S | 3,276,208 | USA | US | NoA |
| Phoenix | PHOE | 33.448376 | -112.074036 | P | 4,948,203 | USA | US | NoA |
| Dallas | DALL | 32.779167 | -96.808891 | D | 1,303,000 | USA | US | NoA |
| Houston | HOUS | 29.749907 | -95.358421 | H | 2,314,000 | USA | US | NoA |
| Miami | MIAMI | 25.761681 | -80.191788 | M | 5,500,000 | USA | US | NoA |
| Orlando | ORLAN | 28.538336 | -81.379234 | O | 2,267,846 | USA | US | NoA |
| Charlotte | CHAR | 35.227085 | -80.843124 | C | 2,805,115 | USA | US | NoA |
| Atlanta | ATLA | 33.753746 | -84.38633 | A | 5,618,431 | USA | US | NoA |
| Las Vegas | LASV | 36.18811 | -115.176468 | L | 2,227,053 | USA | US | NoA |
| San francisco | SANF | 37.773972 | -122.431297 | S | 4,600,000 | USA | US | NoA |
| Salt lake City | SALT | 40.758701 | -111.876183 | S | 1,257,936 | USA | US | NoA |
| Denver | DENV | 39.742043 | -104.991531 | D | 716,577 | USA | US | NoA |
| Nashville | NASH | 36.174465 | -86.76796 | N | 2,072,283 | USA | US | NoA |
| Raleigh | RALE | 35.787743 | -78.644257 | R | 1,509,231 | USA | US | NoA |
| Washington | WASH | 38.889805 | -77.009056 | W | 7,813,000 | USA | US | NoA |
| Boston | BOST | 42.361145 | -71.057083 | B | 4,941,632 | USA | US | NoA |
| Detroit | DETR | 42.331429 | -83.045753 | D | 4,365,205 | USA | US | NoA |
| Saint Paul | SAINT | 44.954445 | -93.091301 | S | 3,690,261 | USA | US | NoA |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Portland | PORTLA | 45.5202471 | -122.676483 | P | 2,512,859 | USA | US | NoA |
| Philadelphia | PHIL | 39.952583 | -75.165222 | P | 6,245,051 | USA | US | NoA |
| Seattle | SEATT | 47.6038321 | -122.3300624 | S | 4,018,762 | USA | US | NoA |
| Vancouver | VANC | 49.246292 | -123.116226 | V | 2,642,825 | Canada | CA | NoA |
| Calgary | CALG | 51.049999 | -114.066666 | C | 1,414,000 | Canada | CA | NoA |
| Edmonton | EDMON | 53.631611 | -113.323975 | E | 1,418,118 | Canada | CA | NoA |
| Toronto | TORON | 43.65107 | -79.347015 | T | 6,712,000 | Canada | CA | NoA |
| Montreal | MONTR | 45.508888 | -73.561668 | M | 4,292,000 | Canada | CA | NoA |
| quebec | QUEBEC | 46.829853 | -71.254028 | Q | 557,390 | Canada | CA | NoA |
| Averdeen | AVER | 57.149651 | -2.099075 | A | 227,560 | United Kingdon | UK | EU |
| Iverness | IVERN | 57.477772 | -4.224721 | I | 55,000 | United Kingdom | UK | EU |
| Norwich | NORW | 52.630886 | 1.297355 | N | 141,137 | United Kingdom | UK | EU |
| Sandnes | SANDN | 58.85326 | 5.73295 | S | 350,000 | Norway | NO | EU |
| Kristiansand | KRISTI | 58.14671 | 7.9956 | K | 155,648 | Norway | NO | EU |
| Östersund | ÖSTE | 63.1792 | 14.63566 | O | 49,806 | Sweden | SE | EU |
| Norköping | NORK | 58.588455 | 16.188313 | N | 93,765 | Sweden | SE | EU |
| Kiruna | KIRUNA | 67.85572 | 20.22513 | K | 18,154 | Sweden | SE | EU |
| Rovaniemi | ROVA | 66.503059 | 25.726967 | R | 64,535 | Finland | FI | EU |
| Kuopio | KUOPI | 62.89238 | 27.67703 | K | 122,594 | Finland | FI | EU |
| Cagliari | CAGLI | 39.227779 | 9.111111 | C | 165,000 | Italy | IT | EU |
| Sassari | SASSARI | 40.725925 | 8.555683 | S | 122,333 | Italy | IT | EU |
| Mahon | MAO | 39.886641 | 4.253336 | M | 29,125 | Spain | ES | EU |
| Palma de Mallorca | PALMAM | 39.571625 | 2.650544 | P | 424,837 | Spain | ES | EU |
| Eivissa | EIVISSA | 38.906986 | 1.421416 | E | 152,820 | Spain | ES | EU |
| Granada | GRANADA | 37.148055 | -3.600833 | G | 233,680 | Spain | ES | EU |
| Murcia | MURCIA | 37.984047 | -1.128575 | M | 459,778 | Spain | ES | EU |
| Brest | BREST | 48.389999 | -4.49 | B | 140,993 | France | FR | EU |
| Zakynthos | ZAKYN | 37.78913845 | 20.79008957 | Z | 40,650 | Greece | EL | EU |
| Agrostoli | AGROSTOLI | 38.173168 | 20.489973 | A | 12,600 | Greece | EL | EU |
| Iraklion | IRAK | 35.341846 | 25.148254 | I | 173,450 | Greece | EL | EU |
| Paros | PAROS | 37.085644 | 25.148832 | P | 13,710 | Greece | EL | EU |

| City | Abbreviation | Latitude (deg) | Longitude (deg) | First Letter | Population | Country | Country (codes) | Continent |
|---|---|---|---|---|---|---|---|---|
| Fira | FIRA | 36.42107 | 25.43087 | F | 2,000 | Greece | EL | EU |
| Kos | KOS | 36.89333 | 27.28889 | K | 33,000 | Greece | EL | EU |
| Rodos | RODOS | 36.17262995 | 27.91941815 | R | 115,000 | Greece | EL | EU |
| Pape’ete | PAPE | -17.535 | -149.569595 | P | 105,128 | Frans-Polynesië | PF | ZoA |
| Malta | MALTA | 35.917973 | 14.409943 | M | 552,747 | Malta | MT | EU |
| Split | SPLIT | 45.508133 | 16.440193 | S | 160,577 | Croatia | HR | EU |

**Table G.1:** City Data in Algorithm

# H

# Detailed results about the effects on hubs

The study presented several maps illustrating the impact of the ban on hubs. These maps are based on the figures shown below, which indicate the increase or decrease in the number of departing passengers for each hub included in this study. These changes are compared to the base scenario and can be viewed for each scenario.


**Figure H.1:** Legend of passengers on hubs figures (Figure H.2, H.3, H.4 and H.5)

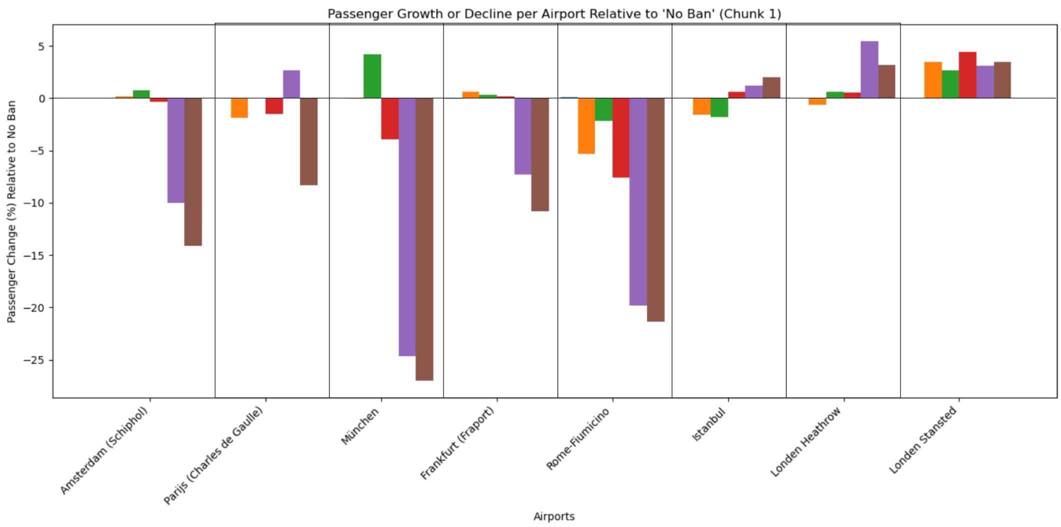


**Figure H.2:** Decreases/increases in departing passengers compared to a scenario without a ban on short-haul flights (Part 1).

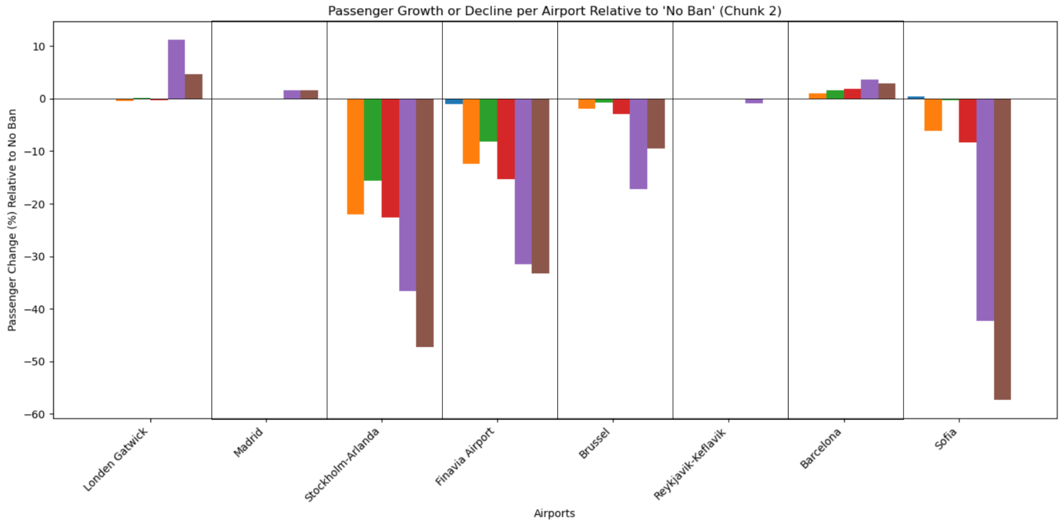


**Figure H.3:** Decreases/increases in departing passengers compared to a scenario without a ban on short-haul flights (Part 2).

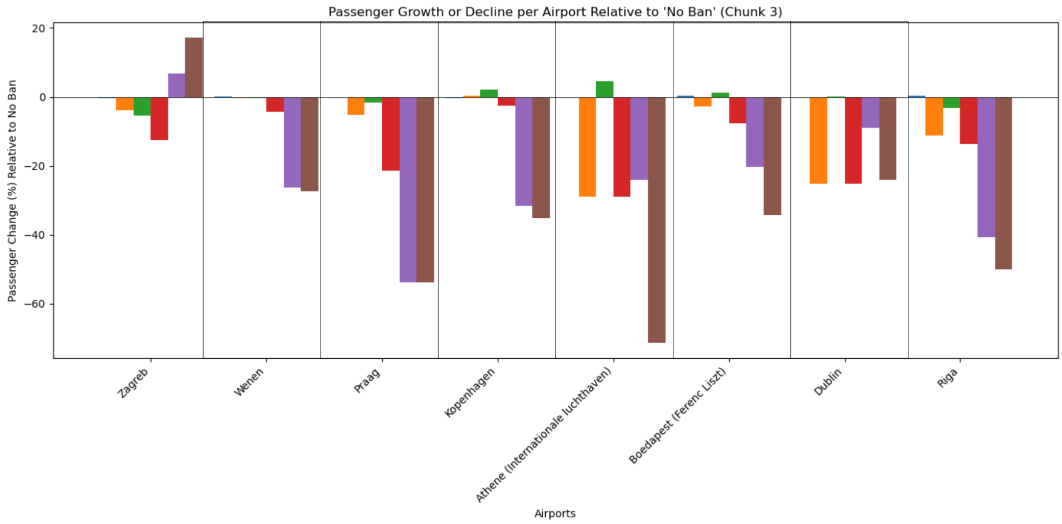


**Figure H.4:** Decreases/increases in departing passengers compared to a scenario without a ban on short-haul flights (Part 3).

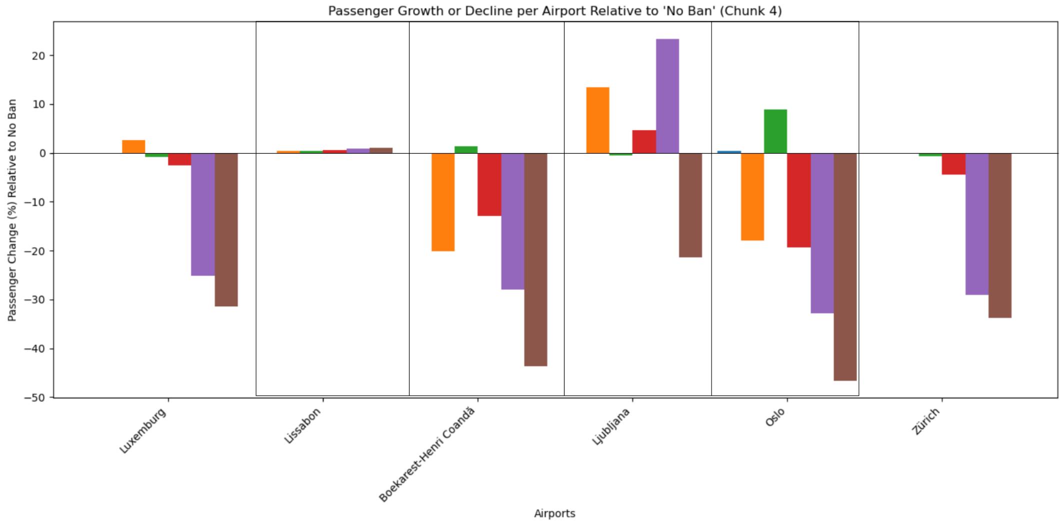


**Figure H.5:** Decreases/increases in departing passengers compared to a scenario without a ban on short-haul flights (Part 4).

# The impact of a ban on short-haul flights on transfer passengers and CO2 emissions

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## Abstract

This study investigates the impact of a ban on short-haul flights in Europe on transfer passengers and CO2 emissions, focusing on both time-based and distance-based bans. Employing a route assignment analysis of a base scenario of Europe with an optimal High-Speed Rail (HSR) netwerk, compared with various scenario's of a ban. Results reveal that the impact of the ban on CO2 emissions is influenced by transfer passengers, primarily due to their average detour distance. The effects on different European hubs vary based on their geographical and operational characteristics. The findings suggest that a time-based ban could contribute to CO2 emission reductions, but more research is needed on the effects of the ban within the current HSR network in Europe. It is clear that the ban will impact hubs, and future research should examine how this will affect connectivity and economies in different regions.

***Keywords: Short-haul flight ban, Transfer passengers, High-speed rail (HSR), Air-Rail integration and Hub & Spoke network***

## I. Introduction

The environmental impact of aviation has become increasingly prominent in policy discussions, especially following the Paris Agreement. In response, the European Union (EU) wants to implement various initiatives aimed at reducing CO2 emissions in the transport sector, with a focus on reducing plane use. The aviation sector leaves a substantial ecological footprint due to the high frequency and energy demands of flights.

At this moment, air travel is the dominant mode of transport for long-distance journeys in Europe. This long-distance air travel can be divided into three types of flights: short-haul, medium-haul, and long-haul. Short-haul flights cover a maximum distance of 1,500 km and are mainly operated by low-cost and regional carriers. These flights are also an important type of flight in the hub-and-spoke network known as feeder flights. Short-haul flights are the most commonly used in Europe, accounting for 74.2% of all flights Dobravsky (2021). In Europe, these flights are responsible for 24.9% of total aviation CO2 emissions, as shown in Figure 1.

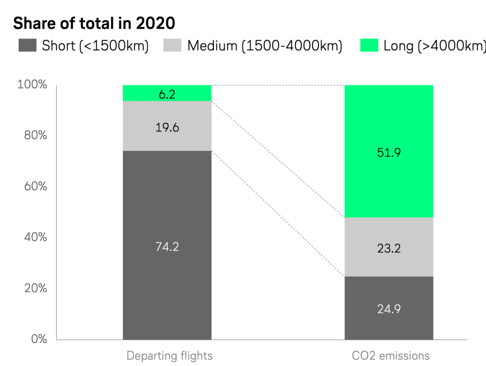


Figure 1: CO2 Short vs Medium vs Long distace flights (Dobravsky (2021))

To mitigate these environmental impacts, a proposed strategy is to integrate High Speed Rail (HSR) into the hub-and-spoke network (Givoni and Banister (2006)). This is because HSR produces less CO2 than planes (Prussi and Laura (2018)). Previous studies have demonstrated the feasibility and environmental benefits of HSR as a substitute for short-haul air travel-particularly for distances under 750 km, where rail is often faster or equally competitive in travel time (Adler et al. (2010)). The effectiveness of this integration is hindered by competition on the same routes between air and rail (Xia and Zhang (2017)). Additionally, many passengers still opt for short-haul flights within the hub-and-spoke network. To promote the use of HSR for shorter distances, the EU could implement a ban on short-haul flights. This would grant HSR a monopoly on certain routes, leading to an increase in passengers on HSR services. Since HSR emissions are lower than those of planes (Prussi and Laura (2018)), this should result in an overall reduction in CO2 emissions in the transport sector.

Despite these prospects, current literature presents mixed findings on the effectiveness of a short-haul flight ban. National case studie from Finland, show a reduction of 95% in Finland due to a ban on short-haul flights (Baumeister and Leung (2020)). A study by de Bortoli and Féraille (2024) shows also a improvement of the HSR average emissions, because more passengers choice the HSR.

There is little research in the current literature on how the ban on short-haul flights will affect the hub-and-spoke network. In particular, the impact of the ban on transfer passengers has not been considered. Transfer passengers originate from the hub-and-spoke network and use multiple flights to reach their final destination. Additionally, the effect of the ban on hubs in Europe has been understudied, as these hubs are central to the network and provide good accessibility to European cities, boosting the local economy (Volkhausen (2022)). It is important to examine how the ban will affect passenger flows through the various hubs. Furthermore, while a possible goal of the ban is to increase air-rail use in Europe, the effects of the ban on air-rail usage remain under explored.

By better understanding these passenger choices, it is possible to form a clearer picture of the ban's impact on aviation CO2 emissions. As the HSR network in Europe is currently not optimally developed and is considered in this study as the main alternative for short-haul flights, this study has chosen to optimise the HSR network in Europe to create a fully functioning HSR network in Europe. This research provides an opportunity to assess the effect of the ban on short-haul flights in Europe, provided that a well-functioning HSR network is in place, which also ensures an effective Air-Rail network. This research was conducted using the following research question and sub-questions.

**How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?**

**Sub-questions:**

- How can a ban on short-haul flights be designed, and what indicators could affect its impact?
- How can a base scenario be developed to research the effects of the ban on short-haul flights?
- How will passenger mode choice affect CO2 emissions in the aviation sector for each type of ban on short-haul flights?
- Does the ban on short-haul flights promote the use of the Air-Rail network?
- How will a ban on short-haul flights change the competitive position of hubs across Europe?

The rest of this paper will first discusses the indicators affecting the ban's effectiveness. Next, it outlines the methodology used in the study, followed by a discussion of various model parameters. This is followed by validation and verification of the model, leading to the results and conclusions. Finally, the paper discusses the findings and offers suggestions for future research.

## II. Ban on short-haul flights

This chapter will examine the implications of the ban on short-haul flights and its effects. It will begin with explaining the current state. After it will explain the design of the ban and how this will effect passenger choices. The chapter will conclude with the different expectations of the results.

### A. Origins of transfer passengers

In the aviation sector, passengers either travel directly or transfer through hubs, depending on airline strategies. Point-to-point carriers prioritise direct routes, often operating as low-cost carriers. In contrast, hub-and-spoke carriers use central hubs to connect regional feeders with long-haul flights, maximising aircraft occupancy and expanding service areas with fewer routes, as illustrated in Figure 2. For this reason, hubs have high connectivity with the world and provide economic benefits to the region around the hub(Volkhausen (2022)). Because transfer passengers must use multiple flights, the routes they travel often cover large flight distances and lead to high CO2 emissions. A key characteristic of such hubs is that they have high global connectivity and serve as a home base for a carrier that employs the hub-and-spoke strategy.

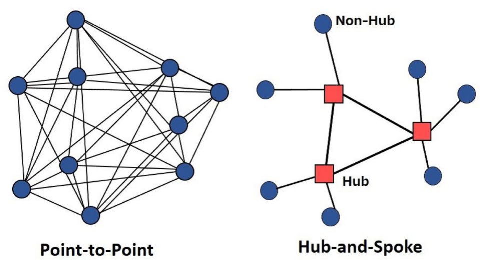


Figure 2: Point to point en hub and spoke design (Kuroki and Matsui (2024))

## B. The passenger choices in the current state

When a passenger wants to travel between two cities, they can choose from several transport options. To give an idea of the options a passenger has, there is made an example of a passenger that wants to travel between New York and Brussels. The various options for a passenger wishing to travel between New York and Brussels are shown in Figure 3

In this example, there are three possible routes a passenger can choose. The first option is a direct flight from New York to Brussels, which is a long-haul flight. The other two options involve transfers. In the first of these, the passenger takes a long-haul flight to Schiphol Airport and then transfers to a short-haul flight to reach the final destination. The last option is a long-haul flight to Heathrow in London, followed by a transfer to a short-haul flight to Brussels.

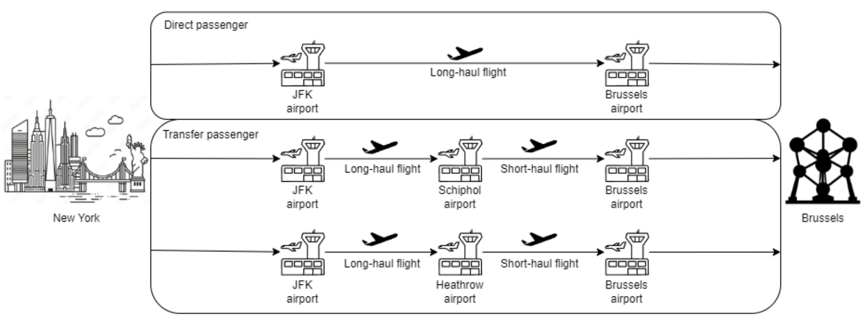


Figure 3: Three options for a passenger to travel between New York and Brussels

## C. Conceptual design of a ban on short-haul flights

A conceptual ban on short-haul flights can be approached in two main ways: a distance-based ban and a time-based ban. The distance-based ban prohibits flights between airports that fall below a specified minimum distance threshold. Its key advantage is simplicity, making it easy for policymakers and airlines to implement. However, this approach fails to account for geographical and infrastructural constraints, potentially limiting city-to-city connectivity when viable transport alternatives, such as rail or road, are unavailable. This could result in significant travel detours and increased emissions, undermining environmental objectives.

The second approach is a time-based ban that considers the availability and efficiency of high-speed rail (HSR) as an alternative. Flights are prohibited only if a train journey between two cities can be completed within a specified time limit. This method incorporates a component that links airports within a 50 km radius of a city, ensuring that policies are more context-sensitive and tailored to actual passenger options. This approach better addresses natural barriers and aims to maintain accessibility while reducing unnecessary short-haul flights.

Despite its benefits, the time-based ban presents implementation challenges. Its complexity requires detailed transport data and accurate assessment mechanisms, increasing the risk of administrative errors. Moreover, it may discourage investment in rail infrastructure, as cities might avoid improving HSR connections to maintain air route viability. Thus, while more equitable and efficient, the time-based ban demands careful governance to balance environmental goals with regional development and transport equity.

### D. Aspects affecting the effectiveness of the ban

The effectiveness of a ban on short-haul flights within Europe is influenced by several factors. Firstly, countries outside the EU pose a challenge, as the EU cannot enforce such a ban in non-member states.These non-EU members fall into three categories: EU candidate countries, Schengen-associated states, and non-EU members. While candidate countries may eventually adopt the ban through EU accession, Schengen-associated states would require individual negotiations but are also likely to implement the ban eventually. Therefore, the countries are considered as those that would implement the ban. Countries like the UK and Turkey, which are not members of the EU, are unlikely to comply, potentially creating opportunities for passengers to detour through hubs in the UK and Turkey. Figure 4 shows the different European countries and the category to which they belong.

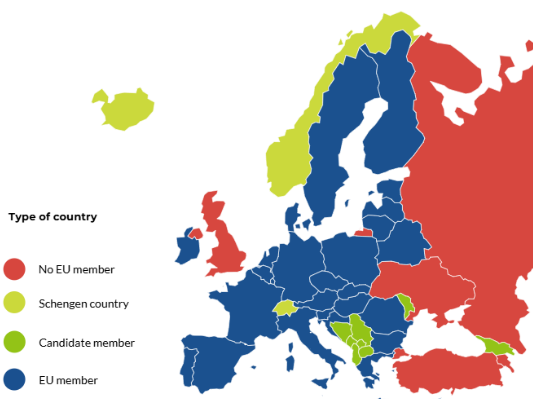


Figure 4: Members of the European Union and Non-EU members

Secondly, the availability and quality of HSR infrastructure play a role in providing viable alternatives to short-haul flights. HSR can effectively replace air travel on routes up to 750 km, but its current coverage in Europe is limited and uneven. High-speed lines require dedicated infrastructure capable of supporting speeds up to 300 km/h, yet many routes still operate on conventional tracks, limiting average speeds and accessibility. As such, a uniform ban without adequate rail alternatives could reduce connectivity for certain regions. For this reason, a fully constructed HSR network in Europe was selected for this study.

Finally, the integration of HSR into the existing air transport system through Air-Rail networks is essential. Seamless transfers between air and rail are facilitated by airport HSR stations, which reduce transit times and improve passenger convenience. When an airport has an HSR station, it is easier for a passenger to transfer from a flight to a train. However, not all major airports in Europe offer such connections. In their absence, passengers must rely on less efficient ground transport, such as taxis, to reach city rail stations, which may discourage the choice of the Air-Rail network. As noted in prior studies, effective Air-Rail integration is key to preserving hub-and-spoke connectivity while promoting sustainable transport modes. It also probably increases the likelihood that a passenger will choose an Air-Rail alternative. This study has therefore linked airports with a train station to the HSR network, despite the current absence of HSR train services at these stations.

### E. Expected effects of a ban on short-haul flights on a passenger

The implementation of a short-haul flight ban in Europe is expected to produce significant shifts in passenger behaviour and transport dynamics. Most notably, the ban will alter route choices for passengers. Figure 5 shows the impact of this ban on the previously mentioned example of a passenger wishing to travel between New York and Brussels. Due to the ban, this passenger can still take a direct flight between New York and Brussels; however, the transfer at Schiphol Airport is no longer available. Passengers can now choose to travel through London Heathrow, which is in the UK and not affected by the ban. This option is not beneficial because the distance the passenger travels will likely increase, leading to higher $CO_2$ emissions. The alternative is to fly to Schiphol Airport and transfer to the HSR, which takes the passenger to Brussels. This means the passenger travels the same distance as before, but by choosing the HSR to reach Brussels, they will produce lower $CO_2$ emissions than taking two flights.

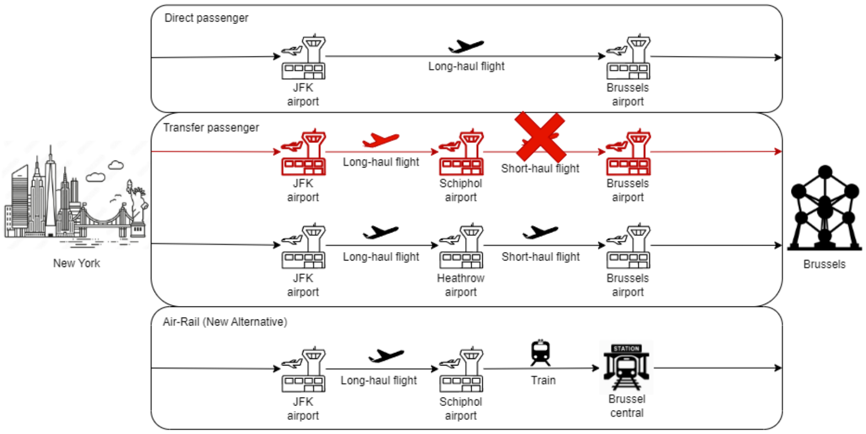


Figure 5: Route options for a passenger travelling between New York and Brussels when a ban on short-haul flights is in effect

A second example illustrates the impact on route choices for a passenger wishing to travel within the limits of the ban. The options for this passenger are shown in Figure 6, which depicts examples of route options between Barcelona and Brussels. As the figure shows, the passenger has a limited set of options available. Due to the ban, the direct flight and transfer flight through Schiphol are no longer viable. Additionally, the Air-Rail alternative is also unavailable for this passenger. Two options remain; the first is to take a flight to Heathrow Airport and transfer to a flight to Brussels. This will result in a high distance travelled by plane, leading to significant $CO_2$ emissions. A cleaner alternative is for the passenger to take a direct train between Brussels and Barcelona, which will have lower $CO_2$ emissions than the transfer option.

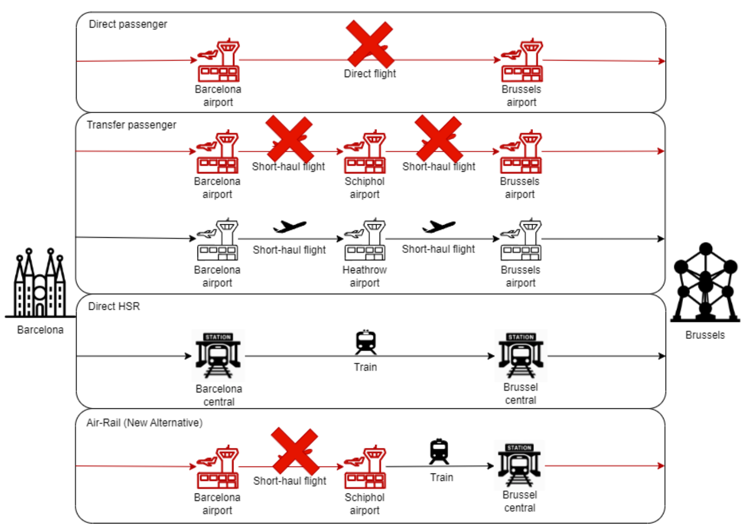


Figure 6: Route options for a passenger travelling between Barcelona and Brussels when a ban on short-haul flights is in effect

## F. The expected global effects of the ban on short-haul flights

The primary objective of the short-haul flight ban is reduce $CO_2$ emissions, by promoting high-speed rail (HSR) usage. Based on Figure 5 and 6, HSR remains a viable option for both long-distance and some transfer journeys, suggesting a likely increase in HSR usage, particularly for direct connections. However, the impact on the Air-Rail network is less certain. While it may benefit long-distance travelers, it becomes unavailable for routes shorter than the ban threshold, potentially limiting its growth.

In aviation, the ban is expected to reduce direct intra-European flights, especially within the hub-and-spoke system where direct options are limited. This may lead to an increase in transfer passengers, including those rerouting through non-EU hubs unaffected by the ban, potentially increasing overall travel distances and associated CO2 emissions. So it is expected that the transfer passengers will influence the impact of the ban on CO2 emissions.

Thus, it can be suggested that the ban on short-haul flights could lead to a reduction in CO2 emissions, provided that the growth in HSR usage compensates for passengers flying around the ban. To assess the feasibility of this, The study has modelled passenger choices under the ban, estimating route selection, hub usage, and resulting aviation emissions to evaluate the policy's overall impact. Thereby, it is assumed that a fully functioning HSR network is in place in Europe.

# III. Method

This section discusses the method used in this study. To calculate passengers' mode choice, several steps were taken, each step consisting of different methods that contribute to the calculations. Since no data on passengers' current mode choices was available, a base scenario was developed first. This section explains how the base scenario was created and the adjustments needed to calculate different scenarios where a ban is implemented. It will also briefly discuss two key methods used in this study: the Frequency-based reallocation method and the random regret method.

## A. Global steps of the base scenario

To calculate the baseline scenario, several steps were taken, as shown in Figure 7. The figure illustrates two distinct calculation streams. The first flow involves calculating demand between cities, which is necessary because the input data comprises flight information between various hubs in Europe. Since the HSR starts and ends in cities, the data must be converted to trips between these locations. Additionally, the input data does not account for transfer passengers, so it is essential to predict the airports between which these passengers intend to travel. This flow is represented by blocks 2 and 3. The second flow involves developing a network, which consists of nodes and edges. Nodes are points where passengers wish to travel; in the model, a node can be either an airport or a city. The edges represent the routes passengers take, and each edge will eventually be assigned a number representing the number of passengers on that route. This flow consists of blocks 4 and 5.

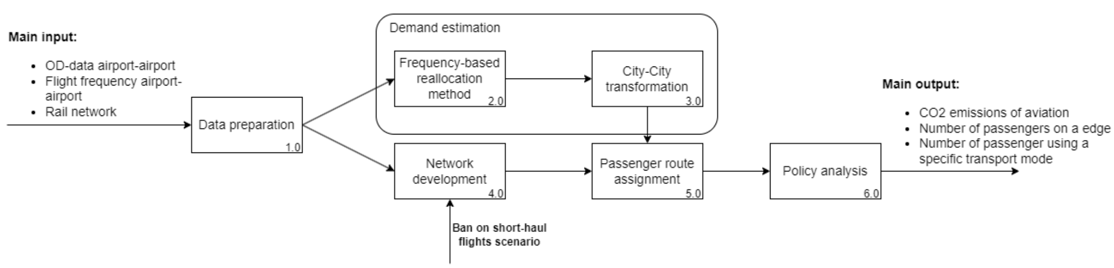


Figure 7: Different steps that the method of this study uses

The input data for this study is sourced from Eurostat (2025) and includes passenger numbers between different hubs for the year 2023. This does not include data for passengers from the UK, which is from 2019, potentially introducing slight bias for UK travelers. However, due to a lack of alternatives, this year was chosen. In addition to passenger numbers, the annual volume of flights between airports is also included, sourced from Eurostat (2025). The final input data consists of an HSR network optimized to connect all cities, with HSR stations added at airports. The HSR connections are based on the study by Grolle (2020) and current infrastructure plans published by Interrail-Eurail (2024).

The first step in developing the base scenario involves calculating various required data, as not all information is available. Therefore, some values are calculated from other accessible data. This includes calculating travel time between two cities by using the haversine method to determine distance and dividing that by the average speed of the respective transport mode. Each travel time also includes constants such as taxi time or transfer time. For HSR, this accounts for potential passenger transfers, while for aircraft, the average taxi time is added to the travel time. The constants used are listed in Table 1. In addition, a list was made of the different hubs that exist in Europe, for each hub there was looked at what the average transfer rates. This data can be found in Appendix A. A hub was selected for each EU country based on accessibility scores from ACI (2024). Some countries were assigned two hubs due to having two major airports.

| What | Value |
|---|---|
| Taxi Time | 15 min |
| Stop Time Train | 15 min |
| Average speed plane | 700 km/h |
| Average speed train | 220 km/h |
| Tolerance level | 50 km |
| Tolerance level non-EU | 100 km |

Table 1: Parameters

At the beginning of this chapter, it was indicated that the data used for this model is from Eurostat (2025) and consists solely of passengers traveling between two different airports. To adjust this data to a format suitable for passengers wishing to travel between two different cities, two steps are necessary. The first step, indicated in block 2.0, is required because the original data does not account for transfer passengers. As a result, passengers taking multiple flights are counted twice. To ensure that each passenger is counted only once in the model, the Frequency-based reallocation method was used. This newly developed method is specifically designed for this study because no existing method was found in the literature that could straightforwardly reallocate transfer passengers to their original origin and destination in an OD matrix.

When the data is adjusted for transfer passengers, it still doesn't indicate the origin or destination of a passenger. In block 3.0, an attempt will be made to assign different passengers to two cities between which they wish to travel. The city-to-city method is from previous research by Grolle (2020). The study by Grolle (2020), which uses the same data format, examines the allocation of passengers to cities. Since both studies are similar, this method can be applied to the current research. However, this study includes passengers traveling from outside Europe. As an adaptation to the original method, these passengers were allocated solely to air travel in the modal split. Additionally, the final step applied by Grolle (2020) was skipped, as including passengers from other transport modes is unnecessary for this study. The same parameters from his study are included in this study. The result of this step is an OD matrix in which passengers are assigned to their desired travel cities.

The initial step in developing the infrastructure begins with establishing the network (block 4.0). In this block, the rail and air networks will merge into a single connected system. This network will consist of various nodes and edges. The nodes represent airports and cities, while the edges represent possible rail or air routes. The value of these edges represents the travel time that is needed to complete a specific edge. Research from Flodén et al. (2017) found that travel costs, travel time, and comfort are the most important factors for passenger route choices. However, because travel costs for plane transport are difficult to estimate, only travel time and a small aspect of comfort were included in this research.

Not all nodes are interconnected; therefore, a car network is included to represent, in some cases, the final leg of travel between a city and an airport. The study focuses on trains and planes, which is why cars are only used to connect cities and airports. While passengers can travel between two cities in Europe by car, it is unlikely they would fly from New York to Schiphol and then drive to Barcelona. For this reason and to simplify the model, car travel is not included on a large scale but is considered only as a means of reaching the airport.

With these networks established, it is time to calculate the likelihood that passengers will choose specific routes. This calculation is conducted in the block entitled Passenger route assignment (5.0).

The first step in block 5.0, is to determine the different routes passengers can take. These routes are searched by using the k-shortest path algorithm, during the search different penalties are added in the algorithm. These penaltie are needed to add realism in the model, a time penalty is added to the total travel time if a passenger makes a specific travel choice in his shortest path. The penalties and their reason can be found in Table 2.

From these routes, a top 5 will be created, which will then be compared with one another. In this comparison, a probability is assigned to each route. The probability is calculated by using the Random Regret method. This probability will then be multiplied by the number of passengers wishing to travel between the cities, allowing us to add the passengers to the different edges they travel.

| No. | Reason for the penalty | Between | Penalty Time |
|---|---|---|---|
| 1 | If an airport isn't a hub | Airport–Airport | +2 |
| 2 | If a taxi ride is taken to a city that isn't the city of the airport, and isn't the final destination | Airport–City – City | +10 |
| 3 | Access time airport with train | City–Airport (with HSR) | +2 |
| 4 | Access time airport with car | City–Airport (no HSR) | +3 |
| 5 | Egress time airport with train | Airport (with HSR)–City | +1.25 |
| 6 | Egress time airport with car | Airport (no HSR)–City | +0.75 |
| 7 | Air–Rail transfer at airport (no HSR) | Plane–Taxi–HSR | +1.5 |
| 8 | Air–Air transfer | Airport–Airport–Airport | +1 |

Table 2: Different penalties in the model

Once passengers are assigned to their edges, the network can be analyzed (block 6.0). The purpose of this analysis is to determine the values of various indicators. This will involve calculating CO2 emissions and examining the number of passengers travelling through each hub to ultimately provide advice to airports. Additionally, it will assess the difference in emissions generated per ban. After completing these steps, the base scenario is created. This base scenario can than be used to compare, with different scenario's in which the ban is implemented.

## B. Frequency-based reallocation method

The passenger data from Eurostat (2025) does not account for transfer passengers, leading to potential double counting in the OD matrix. To make sure the data accounts for transfer passengers, the Frequency-Based Reallocation Method was used. The method reallocates passengers based on the likelihood of transfers, aligning demand with actual origins and destinations.

The method is based on the following idea: If 70 passengers travel from hub A to hub B and 30 passengers travel from hub A to hub C, the probability of a passenger choosing the route to hub B is 70%, while the route to hub C is 30%. This reasoning is based on the principle that routes with more passengers are more attractive, as opposed to those with fewer. Additionally, higher passenger numbers often indicate greater supply. The main purpose of the method is to provide quick and easy insights into the choices of transfer passengers to estimate passenger flows. However, it is not suitable for precise predictions of transport flows. The formulas of the method are shown in Equation 1, 2, and 3.

**Frequency-based demand correction method**

$$N_{ij} + T_{ij} = D_{ij} \quad , \forall i, j \in N \tag{1}$$

$$X_{ij} * (1 - (trans_j * Hub_j)) = N_{ij}, \forall i, j \in N \tag{2}$$

$$T_{ij} = \sum_{n \in N} X_{in} \cdot \text{trans}_n \cdot \text{Hub}_n \cdot \text{Fly}_{inj} \cdot \left( \frac{X_{nj}}{\sum_{m \in N} X_{nm} \cdot \text{Fly}_{inj} - X_{in}} \right), \forall i, j \in N \tag{3}$$

Where:

| Variable | Meaning |
|---|---|
| $N$ | Sets of airports where: $n, j, i \in N$ |
| $D_{ij}$ | Demand between city i and j |
| $T_{ij}$ | Passeners with a transfer traveling between city i and j |
| $N_{ij}$ | passengers traveling without a transfer between city i and j |
| $trans_i$ | Transfer rate at airport i |
| $Hub_i$ | 1 if airport i is a hub zero otherwise |
| $Fly_{i,j,n}$ | 1 if a passenger can transfer towards route n to j , after traveling on route i,n. Zero otherwise |

Formula Equation 1 expresses total demand $D_{ij}$ as the sum of direct passengers ($N_{ij}$) and transfers ($T_{ij}$). Direct demand is computed by removing transfers from the original OD entry (Equation 2). Transfers are estimated using hub status and transfer rates.
Transfer passengers are reallocated based on the probability of continuing to another destination, as

shown in Equation 3. This probability is the share of passengers on a given route relative to all outbound passengers—adjusted by two factors: (1) the feasibility of the transfer, using the Dynamic Restricted Area method (Appendix B), and (2) exclusion of the inbound flight from the probability base. The areas that are prohibit by the Dynamic Restricted Area method can be found in Table 3.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta^{restricted}_{i,n,j}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 3: Restricted areas after different flights

After calculating $N_{ij}$ and $T_{ij}$, the values are summed for each OD pair to obtain the $D_{ij}$. To maintain symmetry, the average of $D_{ij}$ and $D_{ji}$ together is used, resulting in an OD matrix that correctly accounts for transfer passengers. Figure 8 presents a small example that illustrates how the data is adjusted for transfer passengers. In this example, node C is a hub with a transfer rate of 0.4. The example aims to calculate how many passengers travel between airports A and E.

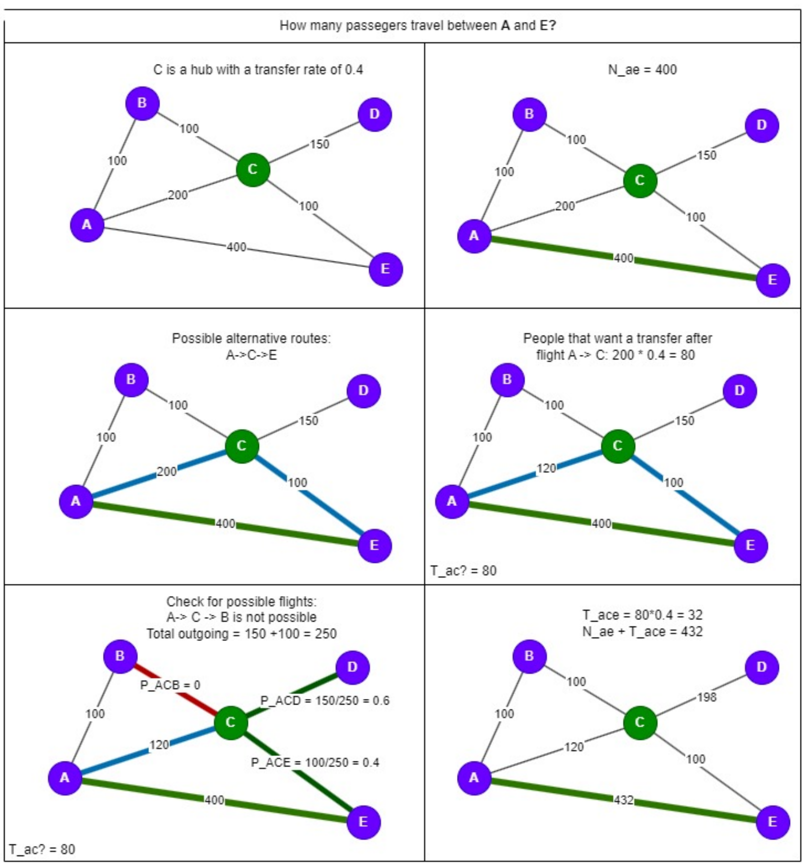


Figure 8: Example: Frequency-based reallocation method

## C. Random Regret method

When the routes are determined and penalties added, there are ultimately five fastest routes for passengers, to travel between two specific cities. With these possible options, it's time to calculate the mode choice using the Random Regret method (RRm). This method is not widely used in similar research, though it is sometimes employed by consultants. Its advantage lies in accounting for the regret passengers feel about unchosen options, unlike the MNL model, which evaluates each route independently without considering other choices. Additionally, the MNL model is challenging to apply when different route options are similar, making the RRm model more effective. Another benefit of this method is that it bases regret solely on the travel time required to complete the route, simplifying its application while accurately estimating the probability of someone choosing a specific route. The used formulas to calculate the RRm are shown in Equation 4 and 5. The only attribute included is the travel time, which is assigned a beta of 0.01. This beta is taken from the study of Grolle (2020), which used this beta for his City-to-City demand estimation.

**Random Regret formulas**

$$R_r = \sum_{n \neq r} \sum_{TT} \ln\left(1 + e^{\gamma TT \cdot (\alpha_{nTT} x_{nTT} - x_{rTT})}\right) - \ln(2), \quad \forall r \in R \tag{4}$$

$$P(r) = \frac{e^{-R_r}}{\sum_{l \in R} e^{-R_l}}, \quad \forall\, r \in R \tag{5}$$

Where:

| Variable | Meaning |
|---|---|
| $R_r$ | Regret value for route option $r$ |
| $\gamma_{TT}$ | Sensitivity parameter for the travel time attribute |
| $\alpha_{nTT}$ | Coefficient associated with travel time attribute $TT$ |
| $x_{nTT}$ | Attribute value of travel time for route $n$ |
| $x_{mTT}$ | Attribute value of travel time for route $m$ |
| $R$ | Set of all available route options |
| $P(r)$ | Change that route $r$ is chosen |

After the probabilities are calculated with the RRm, the passengers can be assigned towards the specific edges they are travelling on. The formula for assigning passengers is shown in Equation 6. At this stage, the probability of a passenger taking the route is multiplied by the number of passengers travelling between the two cities. The number of passengers for each route will then be allocated to the various edges it takes, and this will be done for all the routes. In the end, the number of people travelling over each specific edge will be known. The formula for this step is shown in Equation 6

**Allocation of passengers to different edges formula**

$$f(e) = \sum_{R \in \mathcal{R}_e} P_r \cdot \mathrm{OD}_{i,j}, \quad \forall\, i,j \in I, \tag{6}$$

Where:

| Variable | Meaning |
|---|---|
| $R$ | A specific route |
| $\mathcal{R}_e$ | Set of routes that pass through edge $e$ |
| $P_r$ | Probability of selecting route $R$ |
| $\mathrm{OD}_{i,j}$ | Number of passengers wanting to travel between city i and j |
| $e$ | An edge in the network |
| $f(e)$ | Total passenger flow assigned to edge $e$ |
| $I$ | Set of cities |

Once all passengers are assigned to different edges, this part of the algorithm is complete. From these calculations, a Link Load Matrix is generated, which can then be used to calculate the various indicators, in the policy analysis. This Link Load matrix consists of the amount passengers travelling on edges between different nodes within the network.

## D. Implementing the ban on short-haul flights

This study examines two methods for implementing a ban on short-haul flights: one based on the distance between airports and one based on the travel time compared to High-Speed Rail (HSR). The different scenario's for the ban are calculated using the same steps as the base scenario. Only in the network design (block 4.0 in Figure 7) are adjustments made to calculate the impact of the ban. In this step different travel times of prohibit routes is set to zere. So the k-shortest path algorithm doesn't consider these paths because they aren't there.

The distance-based ban is implemented using a precomputed distance matrix between airports, that is made using the haversine method (block 1.0 in figure Figure 7). A flight is only permitted if the distance between the origin and destination exceeds a specified threshold $Dis_{ban}$. The total travel time $TT_{AB}$ is calculated as shown in Equation 7, and the ban indicator $Ban_{ab}$ determines whether a connection is allowed, as shown in the following equations:

**Distance-based ban calculations**

$$TT_{AB} = \left( \frac{dis_{AB}}{AVE_{ab}^{plane_{speed}}} + T_{taxi} \right) \cdot Ban_{ab} \tag{7}$$

$$Ban_{ab} = \begin{cases} 1, & \text{if } dis_{AB} \geq Dis_{ban} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}$ | Total flight time between airport A and Airport B in hours |
| $dis_{AB}$ | Distance between airport A and airport B in km |
| $Dis_{ban}$ | Distance based ban value in km |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight, 0 otherwise |

The time-based ban compares the flight time to the fastest available HSR route between the city centers associated with the airports. Only EU-internal flights are considered. To allow fair comparison, airports are linked to nearby cities (within 50 km) using the Haversine formula (Equation 10–13). The model checks whether both airports are within range of cities that have HSR connections, using the conditions in Equation 14 and Equation 15. If the HSR journey time $TT_{X_AY_B}^{HSR}$ is shorter than a given threshold $T_{ban}$, the corresponding flight is banned. Otherwise, the flight is allowed or excluded based on the presence of nearby HSR-linked cities, as shown in Equation 16. The full formulation is as follows:

**Time-based ban calculations**

$$TT_{AB}^{Plane} = \left( \frac{d_{AB}}{AVE_{AB}^{plane_{speed}}} + T_{taxi} \right) \cdot Ban_{ab} \tag{9}$$

$$a_{AX} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_A)\cdot\cos(\phi_X)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{10}$$

$$a_{BY} = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_B)\cdot\cos(\phi_Y)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{11}$$

$$d_{AX} = 2r \cdot \arcsin\left(\sqrt{a_{AX}}\right) \tag{12}$$

$$d_{BY} = 2r \cdot \arcsin\left(\sqrt{a_{BY}}\right) \tag{13}$$

$$dis_{AX} = \begin{cases} 1, & \text{if } d_{AX} \leq 50 \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

$$dis_{BY} = \begin{cases} 1, & \text{if } d_{BY} \leq 50 \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

$$Ban_{AB} = \begin{cases} 1, & \text{if } TT_{X_AY_B}^{HSR} \geq T_{ban} \\ 1 - (dis_{AX} \cdot dis_{BY}), & \text{otherwise} \end{cases} \tag{16}$$

Where:

| Variable | Meaning |
|---|---|
| $TT_{AB}^{Plane}$ | Total flight time between airport A and Airport B in hours |
| $TT_{X_AY_B}^{HSR}$ | Travel time between connected city x to airport A and connected city y to airport B |
| $dis_{AX}$ | 1 if city X is in the service area of airport A |
| $T_{ban}$ | Time based ban value in hours |
| $AVE_{ab}^{plane_{speed}}$ | Average speed plane in km/hour |
| $T_{taxi}$ | Taxi time plane |
| $Ban_{ab}$ | 1 if there is not a ban on the flight , 0 otherwise |
| $\phi_1, \phi_2$ | Latitudes of the two points (in radians) |
| $\Delta\phi$ | $\phi_2 - \phi_1$, difference in latitudes |
| $\Delta\lambda$ | $\lambda_2 - \lambda_1$, difference in longitudes |
| $r$ | Radius of the sphere (e.g., Earth's radius) |
| $a_{ax}$ | Intermediate value in the Haversine formula between airport a and city x |
| $d_{ax}$ | Great-circle distance between airport a and city x |

# IV. Policy scenario's and input data

section III has already discussed some of the assumptions of this study, but these are not all the assumptions. This chapter will address the last larger assumptions made in this study. The section will also discuss the different experimental scenarios that are compared with the base scenario.

## A. The correction of input data

The study used large data files from Eurostat (2025), which contain passengers carried on the routes flown from major hubs in Europe. The issue with the data is its size, leading to long calculation times. Therefore, unnecessary data was removed from the model for several reasons.

The first reason airports have been removed is the small flights between Turkish cities. These airports only had flights departing to Turkey. As the study focuses on the impact on the European Union, data from these flights are not relevant. Additionally, the ban will have no impact on these trips, making no difference in the final data. Therefore, it was decided to remove these domestic flights. This decision was also made for international flights from airports that only travelled to Turkey, as they are irrelevant for the same reason.

The dataset used in the study had several limitations and adjustments. Data from the UK dated back to 2019, while the rest was from 2023, due to the UK's departure from the EU in 2020, which ended its obligation to share such data. Unnecessary data was removed from the model, including airports with only flights to the UK and Turkey, as well as some Finnish airports used solely for domestic flights. The study also excluded some European cities to avoid complicating the model without improving the results. Consequently, airports that could not be linked to cities—often located on islands or in areas without high-speed rail stations—were removed to maintain passenger data integrity. Additionally, Soekarno-Hatta International Airport in Indonesia was excluded due to inaccurate data, which showed only one incoming flight when other sources indicated many more, potentially distorting the results.

### B. Emission parameter

To calculate average emissions per passenger, several choices were made. First, an average figure for all flight types was used. Figure 1 shows that long-haul flights emit more than short-haul flights. However, the number of passengers on short-haul flights is expected to fluctuate significantly, while this effect will remain small for long-haul flights. This study primarily focuses on the impact of the ban rather than on precise predictions of the outcomes if the ban is implemented. Therefore, an average number of CO2 emissions per passenger per kilometre was chosen.

The average emissions per passenger per kilometre are based on the emissions of a Boeing 737-400, from a study performed in 2008. This year was chosen due to the availability of data. This narrow-body aircraft has smaller engines and is primarily used for short-haul travel. The selected emission value is 115 g/passenger/km (Carbon Independent (2025)). Note that current aircraft are much cleaner due to innovations in recent years. But this study does not aim to determine an exact emissions figure and focuses solely on comparing CO2 emissions from aviation, after a ban is implemented. Therefore, the value of this data is not crucial for the conclusions.

### C. The design of the HSR infrastructure

Looking at Figure 9, it is noticeable that the European HSR network is not yet fully complete. Additionally, several important connections remain unestablished. Including this network in the study is therefore complicated. This situation necessitates examining the current state of each line and its future prospects.

To maintain simplicity in the study, it will be assumed that the HSR pathway is complete in Europe, this complete HSR network is based on the study of Grolle (2020) that tried to optimize the HSR network in Europe. Furthermore, airports with HSR stations that are not depicted in Figure 9 will also be included. The missing lines and connections between cities are based on the overview of Interrail-Eurail (2024)

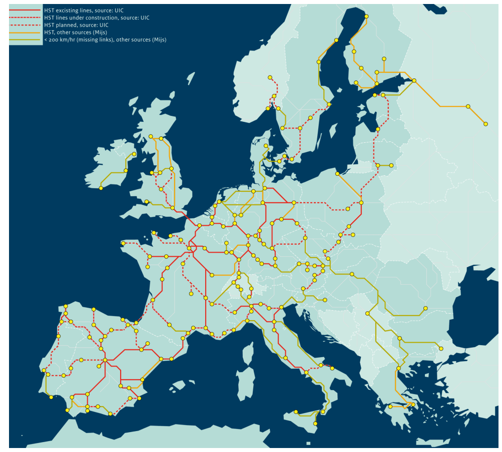


Figure 9: Current HSR network in Europe (Mijs (nd))

The HSR infrastructure used in this study is complete, meaning that all cities in Europe can be reached via HSR, though this does not apply to all airports. Additionally, the study does not consider timetables of train operators; therefore, the travel time of the HSR in the model is sometimes faster than in reality. While this is not true for all routes, it is a common aspect.

### D. Scenario's of the ban on short-haul flights

Currently, several companies and countries have implemented bans on short-haul flights (Wikipedia (2025)). The choice of different policy scenarios is based on the current actions taken by companies or countries. The chosen policy scenarios can be found in Table 4. The aim is to make both types of bans roughly equal. This has been done to ultimately compare which type of ban will be the most effective.

| Scenario | Time-based | Distance-based |
|---|---|---|
| Low | 2.5 hours | 250 km |
| Middle | 6 hours | 750 km |
| High | 14 hours | 1500 km |

Table 4: Different policy scenarios

Starting with the high scenario, the aim is to significantly intervene in the aviation market. This scenario proposes a complete ban on short-haul flights for both types of bans. Figure 1 noted that short-haul flights account for about 24% of total CO2 emissions. A complete ban on short-haul flights with the current HSR network should theoretically reduce emissions by at least 20%. This scenario allows to assess what impact a full ban has on the base scenario, where a full functional HSR network is implemented. With a time-based ban, CO2 reductions will properly be slightly lower than with a distance-based ban, as more routes are permitted under the time-based ban to consider possible alternatives.

For the middle scenario, its based on the study of Adler et al. (2010). According to a study by Adler et al. (2010), his research found that trains are faster than planes till a distance of 750 km. This distance is therefore an interesting benchmark. According to the theory that people always choose the fastest route, this suggests that at this point people should chose 50/50 between air or rail. The question then arises as to whether this holds true if passengers can also fly around the ban. So their can be expected that this scenario is one of the most optimal formats for the ban. The time-based ban will also represent a distance of 750 km. As this means that it would take approximately 6 hours for a person to cover 750 km. The six hours is found by desk research (Google (2025)) different routes, and look how long this takes.

The last and lowest scenario is based on the current policy in France (de Weert (2022)). France has enacted a law, approved by the EU, that bans flights within 2.5 hours of train travel. The purpose of this ban is to eliminate flights within an EU country, as these can be easily replaced by other modes of transport. According to Adler et al. (2010), high-speed rail (HSR) should be significantly faster over this distance. However, the ban can be relatively easy to circumvent. Therefore, it will be interesting to investigate whether this ban will ultimately achieve its intended effect. Desk research indicates that the distance-based ban in this scenario should be 250 km Google (2025).

## V. Verification & validation

This section addresses the verification and validation of the model through a case study using a smaller dataset of transported passengers, as the original model takes too long to run multiple tests. The parameters and track infrastructure are identical to those in the original model. The data used can be found in Appendix C.

Based on the case study results, this section verifies several aspects: the effect of the optimal HSR network, the performance of the reallocation method, and the effectiveness of the ban. It also validates the number of iterations used in the k-shortest path method and the influence of the value of k within this method.

### A. Verification of the HSR network

The model replaces air travel with a High-Speed Rail (HSR) network optimized to provide passengers with unrestricted route choices instead of relying on fixed train lines. This flexibility allows the model to simulate a fully functioning network. Verification was conducted using Google (2025) to compare real public transport times with the model's predictions, which are shown in Table 5. The comparison revealed that the model can predict quicker travel times in some cases, especially in Western Europe. These differences arise because the model does not account for real-world HSR infrastructure complexities, such as the absence of built infrastructure, train speeds, and HSR lines.

Although the model does not fully capture the nuances of real travel behavior, such as long transfer times or inter-station changes in cities like Paris, it generally predicts more favorable travel times for rail compared to reality. Consequently, the model overestimates the attractiveness of HSR, leading to a higher allocation of passengers to trains than would realistically occur. While this enhances the model's competitive positioning of rail over air travel, it also raises concerns about reliability of the model, as the predicted modal shifts are based on an idealized version of the network rather than actual infrastructure constraints.

| **HSR-Route** | **Real time (hour)** | **Model time (hour)** | **Percentage difference** |
|---|---|---|---|
| Amsterdam-Brussel | 2.3 | 1.88 | -18.26% |
| Amsterdam-Barcelona | 11.43 | 9.05 | -20.82% |
| Rome-Barcelona | No train option (17.41 bus option) | 7.21 | -58.59% |
| London-Amsterdam | 4.75 | 3.96 | -16.63% |
| Paris-Lille | 1.03 | 1.26 | +22.33% |
| Paris-Amsterdam | 3.38 | 3.76 | +11.24% |

Table 5: HSR travel times real vs model outcomes (Google (2025))

## B. Verification of the airport reallocation method

A new method has been designed to correct the input data form Eurostat (2025). Important variables from this method are the degrees from Table 3, which are used for the Dynamic Restricted Area. By adjusting various variables, the impact on different routes is examined to determine whether it is justified. The expectation of this test is that the number of passengers wishing to travel between two non-hubs will be significantly influenced by changes in the prohibited area indicators. Additionally, to verify the effectiveness of the frequency-based reallocation method, the direction of routes to the hub must always be negative relative to the input. If this occurs, it indicates that the method is functioning as intended. The results of this verification are shown in Table 6.

| Scenario | Abu Dhabi International Airport → London City | % Difference with Output | Abu Dhabi International Airport → Schiphol | % Difference with Input |
|---|---|---|---|---|
| Input | 0 | - | 197310.00 | - |
| Output | 13264.80 | - | 166508.01 | -15.61% |
| After longhaul flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After longhaul flight transfer to short-haul flight 360° | 11898.84 | -10.30% | 164442.70 | -16.66% |
| After medium flight transfer to short-haul flight 100° | 13726.45 | +3.48% | 166508.00 | -15.61% |
| After shorthaul flight transfer to shorthaul flight 0° | 2764.97 | -79.15% | 164953.30 | -16.40% |
| After shorthaul flight transfer to longhaul flight 360° | 1365.962315 | -89.70% | 163563.5915 | -17.10% |

Table 6: Sensitivity analysis: Restricted area algorithm

As expected, Table 6 shows significant changes in the route between the two non-hub airports. The results indicate that the number of passengers is greatly influenced by changes in the prohibited area. This illustrates that the size of the prohibited area can significantly impact the results of this method. It is difficult to determine whether the chosen values reflect reality, given the results and the fact that not all routes were included in the case study.

Examining the route between Schiphol and Abu Dhabi, it is evident that all values relative to the input are negative. This indicates that fewer people travel on this route, reallocating to other routes. This suggests that the method is functioning as intended. In conclusion, the Frequency-based reallocation method performs as expected, but the Dynamic Restricted Area significantly affects the outcomes.

## C. Validation the number of iterations

Several algorithms are used in this study. Because the shortest path algorithms can get stuck or repeat themselves, a maximum number of iterations was introduced. This allows for a maximum of x steps per route to find a faster option. The maximum is set at 1500 iterations in the base model, meaning that after 1500 steps, the model will proceed to the next route. To verify this number, runs with 500, 1000, 1500, 2000 and 2500 iterations were conducted in the smaller model to analyse sensitivity, the values from the base scenario are compared.

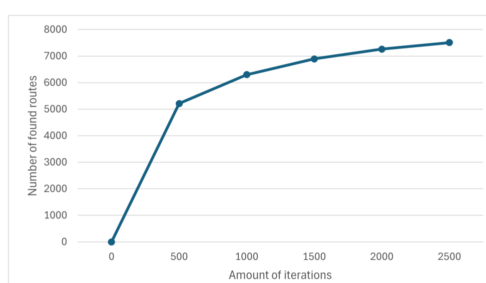


Figure 10: Increasing routes that are found by a higher number of iterations

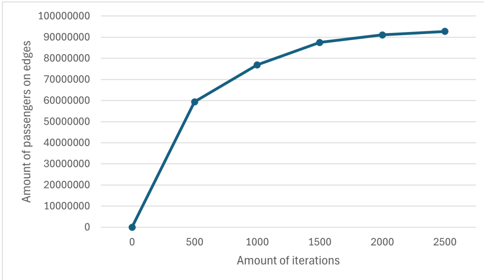


Figure 11: Stabilising number of passengers assigned to different edges with a greater number of iterations.

The issue with the number of iterations is that as it increases, the time required for the model to run rises sharply. Therefore, it is important to select an iteration number that maximizes estimates without significantly increasing the algorithm's computation time. Figure 10 shows that the number of new faster routes does not increase significantly beyond 1500 iterations, although it still rises after that point. This indicates that complex routes can still be found by the model after 1500 iterations. If these routes are selected, the total number of allocated passengers will increase sharply. However, Figure 11 shows that after 1500 iterations, there are not many additional passengers identified by the model. This suggests that while new routes can still be found after 1500 iterations, their usage is very low.

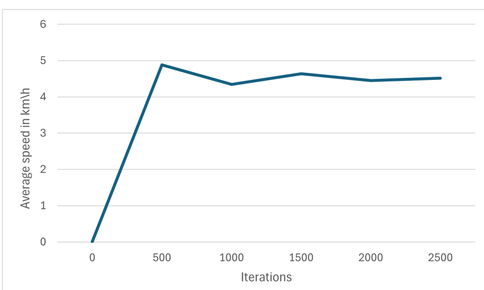


Figure 12: Stabilising average speed with a higher number of iterations.

Further validation using average travel speed was conducted to determine if the model was stuck in a local minimum. The results of this validation are shown in Figure 12. Despite continued increases in the number of iterations, the average speed between city pairs stabilizes around 1500 iterations, indicating that the fastest and most relevant routes have largely been identified by this point. It shows a local minimum at 1000 iterations.

In conclusion, with a limited number of iterations, not all possible solutions can be found. Increasing the iterations beyond 2500 will enhance the number of routes identified, allowing the model to better predict complex routes. After 1500 iterations, only a small group of people are assigned to the newly discovered routes, and hardly any faster routes are found. Therefore, 1500 iterations is sufficient for this study.

### D. Validation of the k value

Within the algorithm, various routes are considered. In the method, there was chosen to examine up to five different routes between cities. The question now is how significant the effect of these chosen routes is on the results. To assess this, different values for k and the total number of passengers assigned to the various edges are analysed.

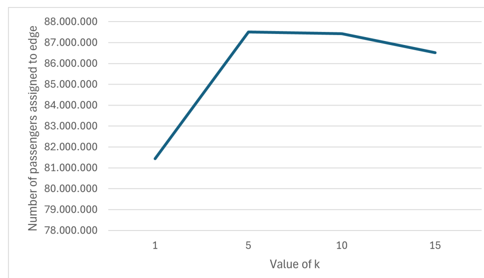


Figure 13: Validation of k-value with the number of assigned passengers

Looking at Figure 13, there is a noticeable difference between a k-value of 1 and 5. This indicates that significantly more complex routes are found, which is not necessarily a drawback. Comparing the k-values of 5 and 10, it can be observed that the increase in routes stabilises. While more routes are identified, this has little effect on the outcomes. Between k=10 and k=5, there is hardly any impact on the results. When k is increased, the results may even decline. This can be attributed to the fact that more routes are selected, causing them to compete for the same passengers. As there is a maximum number of passengers that can be distributed among the different routes, an increase in the number of routes also leads to the selection of longer routes. These longer routes compete with one another for passengers, resulting in a total decrease and making the outcomes appear less reliable. Thus, choosing a k-value of five is not inappropriate.

## VI. Results

This chapter presents the model's results. First, it examines passenger choices in the base case. Next, it compares the results of different scenarios with the base case, focusing on passenger choices for each scenario. It then discusses the impact of these choices on aviation CO2 emissions. Finally, it addresses the effects of the ban on various hubs.

### A. Results of the base scenario

Due to the absence of reference data, a base case was developed. This scenario can be compared with various scenarios where a ban on short-haul flights is in effect. The assessment of the base scenario considers the mode choices made by passengers found by the model, with results shown in Figure 14.

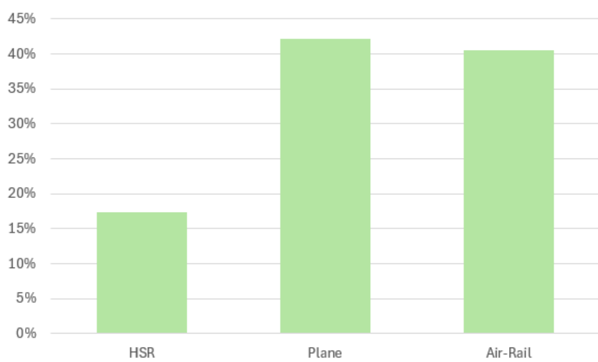


Figure 14: The choices of the passengers in the reference alternative were no ban is applied.

Looking at Figure 14, the key observation is that a group of passengers is already attributed to the HSR, which is noteworthy since the input data consists entirely of air passengers. As discussed earlier, one possible explanation is that this increase results from the presence of a well-functioning HSR infrastructure. This suggests that if the network performs optimally, a significant proportion of passengers traveling within Europe will choose the HSR. Additionally, the Air-Rail network is around 40% in the base scenario, indicating that a well-functioning HSR network can lead to an increase in Air-Rail passengers.

### B. Passenger mode choice with a ban on short-haul flights

The study compared six different bans on short-haul flights with the basescenario, investigating their impact on passenger behavior. In each scenario, the ban is implemented alongside a well-functioning HSR infrastructure in Europe. The results focus on overall modal choice and the effects on direct and transfer passengers, as illustrated in Figure 15 and 16.

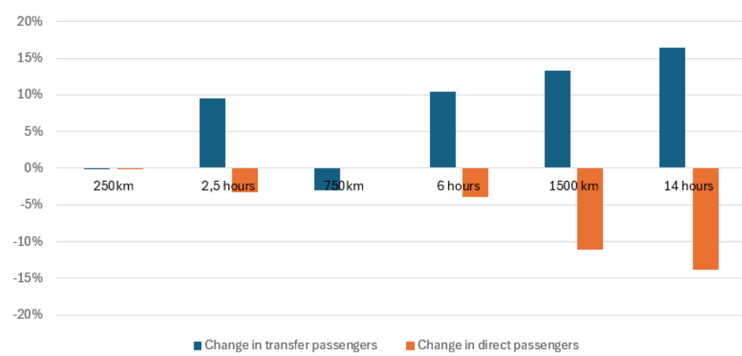


Figure 15: The difference between people choosing to travel directly or via transfer to their final destination, compared to the no-ban alternative.

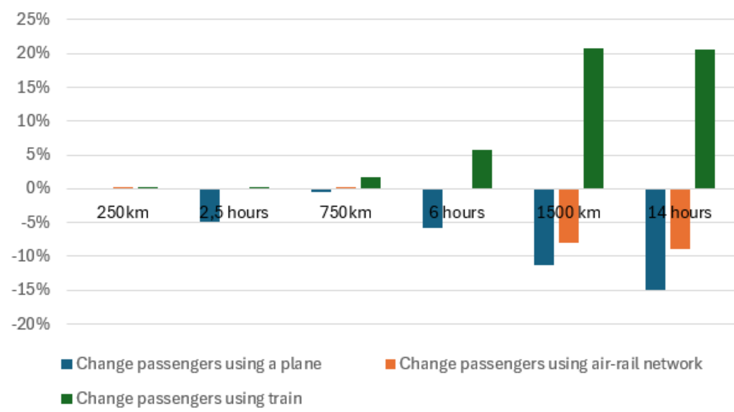


Figure 16: The difference in transport choices by alternative compared to the scenario where no ban applies.

In the 250 km distance-based ban, only minor behavioral changes are observed. A small group of passengers switches from air travel to rail, and there is a slight decrease in transfer passengers and direct passengers. In this scenario, many passengers have likely already switched to the HSR or Air-Rail alternative. This means that the 250 km ban shows little difference from the base scenario, except that the remaining passengers on really short flights are now forced to travel by HSR or take a direct flight. Also there is a small increase in Air-Rail passengers.

Under the 2.5-hour time-based ban, a clearer shift is visible. The number of passengers using high-speed rail (HSR) slightly increases, direct flights decrease, and transfer flights become more common. The number of Air-Rail passengers is slightly decreasing. Importantly, the use of planes decreases by 5% compared to the base scenario. This indicates that the 2.5-hour ban results in a small decrease in plane passengers and an increase in HSR use. However, only the direct use of HSR is growing, not the number of passengers using the Air-Rail network. It implies that passengers are not choosing the Air-Rail option but rather traveling around the ban. This is notable because the use of the Air-Rail network is declining, while the number of transfer passengers is rapidly increasing. The decline in Air-Rail use may be due to the existing fully functional HSR network, leading many passengers with the option of Air-Rail to choose this route already in the base scenario. When the ban has eliminated some routes in this scenario, is it logical that some passengers disappear.

Comparing the 250 km and 2.5-hour bans, it is evident that the 2.5-hour ban had a larger impact on mode choices than the 250 km ban. This effect is also observable when comparing the 750 km and 6-hour bans. In this case, the distance-based ban does not influence passenger choices, while the time-based ban has a larger impact on passenger mode choices.

Overall, the direction of the effects of all four scenarios is the same regarding mode choice. In all scenarios, the use of aircraft decreases while the use of HSR increases. Only the Air-Rail alternative shows differences; notably, the distance-based ban increases Air-Rail use, whereas the time-based ban decreases it. This may be because re-routing is more complicated under the distance-based ban, as there are fewer routes available. Consequently, it is likely faster for a passenger to take the HSR after a flight than to fly around the ban. So it seems that the flying distance of the detour influences passengers' choice behaviour. However, the average distance passengers have to detour was not determined in this study.

With the 750 km ban, passenger behaviour shifts different than the time-based alternatives. There is a reduction in transfers within Europe and increased HSR usage. Also the usage of Air-Rail is increasing slightly, but this is very limited. The 6-hour ban shows further growth in HSR usage, as seen in the 2.5-hour scenario. Additionally, the number of transfer passengers is increasing, with a small reduction in direct passengers. This indicates that some passengers are attempting to fly around the ban. This is likely easier in the 6-hour scenario than in the 750 km scenario because more flight paths remain available in the 6-hour scenario. In the 750 km scenario, there is a decrease in transfer passengers, indicating that it is more challenging to travel around the ban in that scenario.

The results of the 1500 km and 14-hour bans look very similar. Both show a decrease in direct passengers and an increase in transfer passengers. However, the time-based ban has a larger impact on passenger choices than the distance-based ban. This differs when examining mode choices, as the number of HSR passengers grows slightly more under the distance-based ban than under the time-based ban. Notably, the use of the Air-Rail network in both types of scenarios decreases by more than 5%, indicating that a ban on short-haul flights will reduce the use of the Air-Rail network, while passenger choices seem to be shifting toward the direct HSR alternative.

## C. The impact on CO2 emissions

To say something about the CO2 emissions of aviation after the introduction of a ban on short-haul flights, the average difference compared to the reference alternative was considered. Using these results, an attempt is made to illustrate the impact of various scenarios of the ban on CO2 emissions in the aviation market. Figure 17 shows the different result about the CO2 emissions.

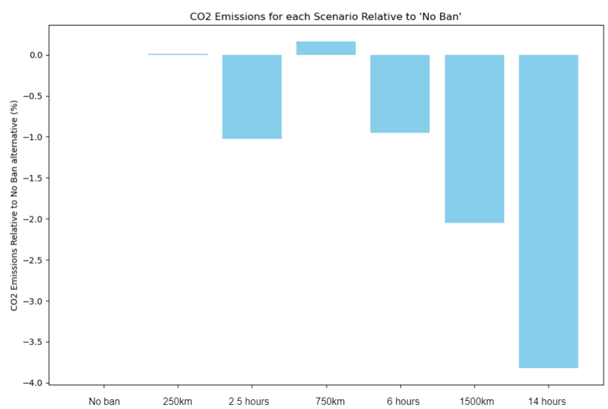


Figure 17: The difference in CO2 emissions based on the No Ban scenario, where no ban on short-haul flights is in place.

The first thing to notice is that when the ban is set at 250 km or 750 km, CO2 emissions do not decrease; in fact, they slightly increase compared to the base scenario. Examining passenger mode choices reveals that these two scenarios have little impact on mode selection. However, when comparing mode choices with CO2 emissions, it is evident that the group flying now takes larger detours, resulting in increased CO2 emissions. This is likely due to the design of the ban, as it does not consider possible HSR routes. As a result, a passenger may need to travel around the ban, likely increasing the flight distance they must cover. This suggests that a passenger's detour distance impacts CO2 emissions.

In the time-based scenarios, particularly the 2.5-hour and 6-hour bans, there is a slight decrease in aviation CO2 emissions. Notably, the 2.5-hour ban results in a greater reduction in CO2 than the 6-hour ban. In both time-based scenarios, the number of HSR passengers is increasing, suggesting that removing plane options on competitive HSR routes leads to a reduction in CO2 emissions. It is important to note that in the base scenario, a fully functional HSR network is used, so the train competes with planes on more routes than in reality.

Considering the two extreme alternatives, the 1500 km and 14-hour bans effectively eliminate short-haul flights. The reduction in CO2 emissions from aviation due to these bans is modest compared to the base scenario, yielding a maximum reduction of only 4% for the 14-hour ban, while the 1500 km scenario shows a reduction of 2%. This indicates that even with a fully functional HSR infrastructure, a complete ban has a limited impact on CO2 emissions. However, it may be that much of the CO2 emissions have already been reduced by the base case; as a result, the emission reductions due to the ban are relatively low. This indicates that, once a fully functioning HSR network is available in Europe, a ban on short-haul flights has a minimal effect on further reduction of CO2 emissions from aviation.

Revisiting the structure of both types of bans in the complete ban scenario, it can be observed that the time-based ban restricts fewer routes. Consequently, there are more flight options available to passengers, resulting in a shorter distance for rerouting. This is in contrast to the distance-based ban, which has a higher average detour distance and fewer transfer passengers. Since the time-based ban leads to a greater reduction in CO2 emissions, it is evident that a balance must be struck between the extent of the ban and the average detour distance for passengers. This variable is likely to have a more significant impact on CO2 reduction than the number of transfer passengers. The variable of average detour distance was not examined in this study.

## D. Impact of the ban on the different hubs

In addition to the overall CO2 picture, this study aimed to map the impact of the ban on various European airports, focusing on hubs. This was achieved by comparing the total departing passengers from the hubs in each scenario with the number from the base scenario. The effect on each hub was analyzed for each scenario, resulting in a global overview. This overview is illustrated in Figure 18, which displays the ban's effect on the different hubs.

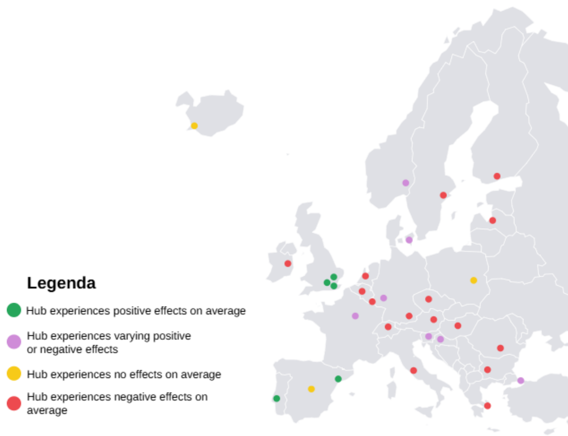


Figure 18: The average effect of the ban on different hubs around Europe.

The effects of various short-haul flight bans on airport hubs reveal significant variation compared to the base scenario. Smaller airports—such as Prague, Riga, Sofia, and Budapest—experience the most notable declines in passenger numbers under larger ban scenarios. While changes are minimal under a 250 km ban, greater distance- or time-based restrictions can lead to reductions in passenger volumes of up to 50% in some cases. These effects are especially evident at airports with limited intercontinental connections or smaller hubs.

In contrast, Ljubljana, another smaller airport, shows moderate passenger increases under specific scenarios but also significant decreases under certain time-based scenarios. This is likely due to the small input data, which increases the impact on this hub. Reykjavik-Keflavik remains largely unaffected across all scenarios, reflecting its geographic isolation and minimal exposure to short-haul traffic.

Larger hubs such as Schiphol, Frankfurt, and Munich initially experience growth in passenger numbers under moderate bans (250 km or 2.5-hour), likely due to their robust intercontinental networks and their role as transfer nodes, allowing passengers to bypass affected short-haul routes. However, with more extensive bans (e.g., 6-hour or 1,500 km), even these airports show declines compared to the base case. Regional context and geographic location also influence outcomes: southern airports like Barcelona and Madrid exhibit growth under most scenarios, possibly due to their peripheral location, which limits the number of affected routes. Non-EU hubs in London and Istanbul see moderate increases in passenger numbers compared to the base scenario. Overall, the analysis underscores that hub responses to short-haul bans are highly sensitive to location and previous connectivity prior to the ban.
Compared to the base scenario, it is evident that implementing a ban leads to a loss of passengers at several hubs within EU countries. On its own, this is not an issue, as the aim of the policy is to encourage more passengers to choose HSR. What is striking is that with any kind of ban, the EU can be divided into regions where one hub experiences an increase in passenger numbers while other hubs in the area lose passengers. This suggests that the location of a hub plays a significant role in the impact of the ban. If a hub's location allows it to maintain more flight routes, it tends to attract more passengers. The study did not examine how many routes a hub retains after the introduction of a ban, but it is noteworthy that hubs that have high connectivity in the base scenario in particular, experience an increase in some scenarios.

## VII. Conclusion

The aim of this study was to investigate how passenger mode choices would influence the impact of a ban on short-haul flights, assuming that the European HSR network is fully developed and functioning effectively. Previous research primarily focused on short trips and individuals wishing to travel within the distance of the ban. Therefore, this study also examined whether transfer passengers influence the impact of the ban and how hubs in Europe are affected by it. Finally, it investigated how the ban affects CO2 emissions from aviation in Europe. All of this was based on the following research question.

**How will a ban on short-haul flights impact the utilisation of hub airports and CO2 emissions in Europe, considering transfer passengers and a fully developed high-speed rail infrastructure?**

The study compared the ban with a baseline scenario in which a fully functional HSR network was constructed. This baseline scenario produced interesting results. The input data consisted entirely of airline passengers. The results showed that by optimising the HSR route, some passengers were already willing to use HSR as a mode of transport instead of aircraft. The proportion of passengers using the Air-Rail network also increased. Therefore, the results indicate that by improving the HSR network, some passengers would choose not to use an aircraft. However, this does not mean that the proportion willing to choose the optimised HSR network would actually make that choice. The study based passenger choices solely on travel time with minimal consideration for comfort; travel costs were not included. Furthermore, the effect of this optimisation on CO2 emissions compared to reality was not examined. The only conclusion that this research can draw in this area is that by optimising the HSR network, there is a good chance that a proportion of passengers will be prepared to use the HSR instead of the plane.

The ban on short-haul flights has been developed in two different ways in this research: a ban based on time and a ban based on distance. The results show that only the time-based ban results in a reduction in CO2 across all scenarios. With the distance-based ban, this only occurs with a complete ban on short-haul flights. This indicates that when there is a well-functioning HSR network in Europe, a time-based ban can still lead to a reduction in CO2 emissions from aviation. However, it has not been investigated whether this is also the case if the current HSR network is applied in the research.

Previous research paid little attention to the effect of transfer passengers on the impact of the ban on CO2 emissions. This research shows that these transfer passengers do influence the impact of the ban, particularly evident in the 250 km scenario. In this scenario, there is little change in passengers' choice behaviour, yet CO2 emissions from aviation still increase. As HSR use increases and direct passengers decrease, the results show that the increase in CO2 must be due by transfer passengers.

Examining the differences in behavioural choices of passengers under a time-based ban versus a distance-based ban reveals that a time-based ban leads to a faster growth in transfer passengers, while this is not the case with a distance-based ban. The research demonstrates that transfer passengers influence the impact of the ban on CO2 emissions from aviation, but this does not depend on the number of passengers, rather on the average distance a transfer passenger must cover due to the ban.

For the Air-Rail network, this research shows that by optimising the HSR network, utilisation of this network increases significantly. The study cannot confirm whether this is due to HSR stations at airports, but it is likely that this plays a role. At the time the ban is implemented, there will be little increase in passengers on the Air-Rail network. It is more likely that there will be a decrease in Air-Rail use. This does not have to be detrimental; if passengers switch to HSR, it can still lead to a reduction in CO2 emissions.

The impact of the ban varies among different hubs and depends on specific scenarios. Notably, the impact depends on the location and size of the airport before the ban is implemented. These two factors influence the connectivity of a hub when a ban on short-haul flights is enacted; a hub with high connectivity after the implementation of the ban has a greater chance of experiencing an increase in passenger numbers. This research cannot say whether the hubs will disappear due to the ban, but it does indicate that the impact on some hubs could be significant.

In conclusion, this study shows that when Europe has a well-functioning HSR network, a time-based ban on short-haul flights can still lead to a small reduction in CO2. The impact of this ban is influenced by the route choices of transfer passengers and the distances they must detour. Air-Rail use will not significantly increase when the ban is implemented if a good HSR network is already in place, it is more likely to decrease. Additionally, the ban will have a considerable negative impact on passenger numbers in several smaller hubs within EU member states, but whether these hubs will also disappear remains uncertain. Thus, a ban on short-haul flights will affect the EU, but it is questionable whether this impact is desirable.

## VIII. Discussion & Future research

This study is the first to use this method to predict passengers' behavioral choices during a ban on short-haul flights. The method primarily focused on passengers' transfer times, excluding travel costs. The findings indicate that when a well-functioning high-speed rail (HSR) network exists in Europe, some passengers are willing to choose HSR. However, it remains uncertain whether this holds true when travel costs are factored in. In order to get a good picture of the effects of the ban on Europe in the presence of a well-functioning HSR network, it remains therefore still relevant to examine how travel costs influence passenger choices.

This study assumes that a well-functioning HSR network is being developed in Europe. Using a baseline scenario in which this network has been established, different scenarios have been compared. Previous research by Baumeister and Leung (2020) indicated that a study in Finland, where a ban was implemented, would result in a 95% reduction in CO2 emissions in the transport sector. In Baumeister and Leung (2020) study, the possible alternatives for passenger transport consisted of the existing national train network. When comparing this study with Baumeister and Leung (2020) findings, it can be argued that a ban on short-haul flights would reduce CO2 emissions in the aviation sector in Europe. However, this will be influenced by transfer passengers, which could result in an increase in CO2 emissions due to the ban. While Baumeister and Leung (2020) study suggests that a ban on short-haul flights could significantly affect CO2 emissions in the transport sector, this study indicates that, if the ban is implemented at a European level, transfer passengers may negatively affect CO2 emissions. As this study does not utilise the current HSR or train network, it remains unclear how the reduction in CO2 emissions would be. It may therefore be worthwhile to repeat this study using the existing HSR network in Europe.

The study shows that transfer passengers influence the effectiveness of the ban on short-haul flights. To determine which type or size of ban will positively impact Europe, the study revealed that this depends not on the number of transfer passengers but on the average distance they must detour. While the number of transfer passengers may still play a role, it is less significant than distance. This study identified a connection between these two variables and the overall CO2 reduction resulting from the ban. The results are considered logical and do not indicate to come from an error in the model. Therefore, it can be expected that the average detour distance of transfer passengers will also play a role in reality. It may still be worthwhile to explore the relationship between the average detour distance of transfer passengers and the number of transfer passengers in a potential follow-up study. This could help identify which type and size of the ban would lead to a reduction in CO2 emissions in Europe. The expectation is that if these two variables are balanced, a scenario can be found that maximises CO2 reduction if a ban on short-haul flights is implemented in Europe.

In Europe, the ban appears to redistribute passengers, particularly affecting smaller hubs. The study indicates that fewer passengers will travel from various European hubs, leading to decreased turnover at these hubs and raising concerns about the potential disappearance of some. It is clear that the ban will impact hubs, and future research should examine how this will affect different regions connectivity and economical.

## A. The limitations of the model

The study had two major limitations that could have affected the results. The first was the lack of available data on passenger demand between different cities. To estimate how many passengers wanted to travel between cities, data from Eurostat (2025) was used, indicating the number of passengers who travelled between two airports in 2023. The issue with this data is that it does not account for transfer passengers, leading to double counting. To allocate these transfer passengers to their original departure and destination, the Frequency-based reallocation method was employed.

The Frequency-base reallocation method was specifically developed for this study and has not been used before in existing literature. However, it only considers departing passengers and potential illogical transfers, neglecting other possible factors. For instance, passengers may choose specific airlines or alliances. If an airline operates a hub-and-spoke strategy, the likelihood that a passenger will fly to the airline's home hub is significantly higher than on the largest route departing from a specific airport. Therefore, it would be beneficial for future research to explore whether these airlines or alliances can influence the frequency-based reallocation method to better explain passenger travel behaviour.

Another major limitation of this study was the computing power used to calculate the algorithm. To minimise computing time, a maximum number of iterations was set for the k-shortest path algorithm. Consequently, the algorithm could not calculate all possible route options. As a result, some more complicated routes for passengers may not have been identified, leading to an overestimation of the number of passengers using certain routes. When interpreting the data, it is important to recognise that this model did not predict a future scenario that corresponds 100 per cent to reality.

## B. Future research

Based on the discussion and conclusion, several suggestions have been identified that may be worth investigating in future research. Below is a list of the various suggestions for future research arising from this study.

- What is the average detour distance for transfer passengers when a ban on short-haul flights is implemented in Europe?
- How will the ban on short-haul flights impact CO2 emissions in aviation, assuming the current HSR infrastructure is used as an alternative?
- How will travel costs influence passenger choices when the HSR infrastructure is optimally developed?
- What are the economic consequences for hub regions when a ban on short-haul flights is implemented in Europe?
- How can airline routes be incorporated into the frequency-based reallocation method?

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# Appendix A Hub information

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source transfer-ratings |
|---|---|---|---|---|---|
| Amsterdam (Schiphol) | EHAM | 36.3% | Yes | 75 min | Schiphol Airport (2024) |
| Brussels | EBBR | 14% | Yes | 75 min | Brussels Airport (2023) |
| Munich | EDDM | 45% | No | 90 min | Munchen Airport (2024) |
| Sofia | LBSF | 0.9% | No | 90 min | Sofia Airport (2023) |
| Zagreb | LDZA | **0.9%** | No | 90 min | Based on Sofia airport |
| Vienna | LOWW | 22.41% | Yes | 75 min | Flughafen Wien (2024) |
| Prague | LKPR | **0.9%** | No | 90 min | Based on Sofia |
| Copenhagen | EKCH | 21.67% | Yes | 75 min | Copenhagen Airport (2024) |
| Helsinki (Finavia) | EFHK | 10.92% | No | 90 min | Finavia (2024) |
| Paris (Charles de Gaulle) | LFPG | 20% | Yes | 75 min | Groupe ADP (2024) |
| Frankfurt (Fraport) | EDDF | 50% | Yes | 75 min | Fraport (2024) |
| Athens (Athens Intl) | LGAV | 18.6% | Yes | 75 min | Athens International Airport (2024) |
| Budapest (Ferenc Liszt) | LHBP | **0.4%** | Yes | 75 min | Based on NACO |
| Reykjavik-Keflavik | BIKF | 27% | No | 90 min | Isavia (2024) |
| Dublin | EIDW | 3.4% | No | 90 min | DAAgroup (2024) |
| Rome-Fiumicino | LIRF | **22.41%** | Yes | 75 min | Based on Flughafen Wien (2024) |
| Riga | EVRA | **0.9%** | Yes | 75 min | Based on Sofia |
| Luxembourg | ELLX | **0.9%** | No | 90 min | Based on Sofia |
| Warsaw-Chopin | EPWA | 26% | No | 90 min | Warsaw Chopin Airport (2024) |
| Lisbon | LPPT | **20%** | No | 90 min | ACI (2024) based on Rome and Athens airport |
| Bucharest-Henri Coandă | LROP | **0.9%** | No | 90 min | Based on Sofia |
| Ljubljana | LJLJ | **0%** | No | 90 min | Based on the possible routes and airlines |
| Madrid | LEMD | **33%** | No | 90 min | Based on NACO |
| Stockholm-Arlanda | ESSA | **7%** | Yes | 75 min | Based on 0.5 * Brussels airport |
| Barcelona | LEBL | **4.9%** | No | 90 min | Based on NACO |

Table 7: Information about major hubs in the European Union

| City | Airport code | Transfer rate | Train station | Transfer-time train and plane | Source |
|---|---|---|---|---|---|
| Istanbul | LTFM | **58.1%** | No | 90 min | Based on NACO |
| Oslo | ENGM | **13%** | Yes | 75 min | Based on NACO |
| Zurich | LSZH | 29.7% | No | 90 min | Zurich Airport (2024) |
| London Gatwick | EGKK | **14%** | No | 90 min | Based on Brussels |
| London Heathrow | EGLL | **24.6%** | No | 90 min | Based on NACO |
| London Stansted | EGSS | **7%** | No | 90 min | Based on Stockholm airport |

Table 8: Information about major hubs outside the European Union (highligted numbers are estimated)

# Appendix B Dynamic Restricted Area

This study uses a Frequency-based reallocation method, which examines the probability that a person will switch to another route. To make this method more realistic, a control is needed that checks whether a switch is logical. The Dynamic Restricted Area method is used for this purpose. This appendix provides a detailed explanation of how this method works, illustrated with an example. The formulas for this method can be found in **??**.

## A Example

To explain the method, an example will be used. This example involves a passenger who just arrived at Schiphol Airport after a flight from Athens. The passenger wants to transfer to a new flight, and the question is which route is available for the transfer. From Schiphol, the passenger has three possible options: Abu Dhabi, London, and New York. The coordinates (latitude and longitude) of these locations are listed in Table 9.

| **Airport** | **Latitiude** | **Longitude** |
|---|---|---|
| Schiphol | 52.3086 | 4.76389 |
| Eleftherios Venizelos International Airport | 37.93640137 | 23.94449997 |
| John F Kennedy International Airport | 40.6398 | -73.7789 |
| Sharjah International Airport | 24.433 | 54.6511 |
| London Heathrow Airport | 51.4706 | -0.19028 |

Table 9: Locations of the different airports for the example

The first step to check which transfers make sense is to evaluate the distance the passenger has already traveled and the distance to any new locations. This information helps determine whether the flight is long-haul, medium-haul, or short-haul, which is crucial for the next step. The distance is calculated using the Haversine formula. After calculating the distances,the flights are categorized.

| **From** | **To** | **Distance (km)** | **Type of flight** |
|---|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 2176 | Medium-haul flight |
| Schiphol | JFK (John F. Kennedy) | 5857 | Long-haul flight |
| Schiphol | Sharjah | 5161 | Long-haul flight |
| Schiphol | London Heathrow | 370 | Short-haul flight |

Table 10: Type of flights and distances between the airports

After calculating the distance and labelling the flights, it is time to examine the specific routes and the size of the area that prohibits passengers from transferring. In the study, this was achieved by assigning specific circle sizes to flight sequence types. Table 11 provides a small example of how this table should be interpreted. First, the flight that the passenger took to reach the hub is considered. In this example, the passenger arrived at Schiphol after departing from Athens, which is classified as a medium-haul flight. A possible option for the passenger is to transfer to JFK. Table 10 indicates that the flight from Schiphol to JFK is a long-haul flight. Adding these two flight types together, Table 11 shows that the variable $\theta_{i,n,j}^{restricted}$ takes the value of 90. This means that the prohibited area is

90 degrees wide, making it illogical for the passenger to transfer to a flight within a 90-degree radius of the flight between Schiphol and Athens.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 11: Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow JFK$

In addition to the transfer to JFK, this example also offers the option of transferring to Sharjah. For this flight, the variable $\theta_{i,n,j}^{restricted}$ is identical to that for the transfer to JFK. However, the transfer to Heathrow is different. The flight between Schiphol and London is a short-haul flight, while the other is a long-haul flight. Consequently, the variable $\theta_{i,n,j}^{restricted}$ must assume a different value. This value can be found in Table 12, resulting in a final value of zero for the variable $\theta_{i,n,j}^{restricted}$.

| **Before transfer type of flight** | **After transfer type of flight** | $\theta_{i,n,j}^{restricted}$ |
|---|---|---|
| Long-haul | Long-haul | 90 |
| | Medium-haul | 60 |
| | Short-haul | 0 |
| Medium-haul | Long-haul | 90 |
| | Medium-haul | 120 |
| | Short-haul | 0 |
| Short-haul | Long-haul | 0 |
| | Medium-haul | 120 |
| | Short-haul | 360 |

Table 12: Example of how to read the table for route $Athens \rightarrow Schiphol \rightarrow Heathrow$

The final step of the preparation is to calculate the direction of the various routes. This direction is determined using the Azimuth formula. When applied to the example, the results shown in Table 13 and 14.

| **From** | **To** | $\theta_{i,n}(^\circ)$ |
|---|---|---|
| Athens (Eleftherios Venizelos) | Schiphol | 322 |

Table 13: Direction of the route between Athens and Schiphol

| **From** | **To** | $\theta_{n,j}(^\circ)$ | $\theta_{i,n,j}^{restricted}$ $(^\circ)$ |
|---|---|---|---|
| Schiphol | JFK (John F. Kennedy) | 292 | 90 |
| Schiphol | Sharjah | 118 | 90 |
| Schiphol | London Heathrow | 250 | 0 |

Table 14: Direction and the restricted area for possible transfers after the flight from Athens to Schiphol is taken

The ultimate goal of this method is to assign the variable $Fly_{i,n,j}$ a value of 1 or 0. This value can be used in the Frequency-based demand correction method. To determine whether $Fly_{i,n,j}$ should be 1 or 0, the area where the passenger is not allowed to transfer must first be calculated. Equation 17, 18, 19, 20 and 21 are used for this calculation.

**Formulas Dynamic restricted area calculations:**

$$Fly_{i,n,j} = \begin{cases} 1, & \text{if } \theta_{i,n,j}^{start\_restiction} \leq \theta_{n,j} \leq \theta_{i,n,j}^{end\_restriction}, when: \theta_{i,n,j}^{start\_restiction} \leq \theta_{i,n,j}^{end\_restriction} \\ 1, & \text{if } \theta_{i,n,j}^{start\_restiction} \geq \theta_{n,j} \geq \theta_{i,n,j}^{end\_restriction}, when: \theta_{i,n,j}^{start\_restiction} \geq \theta_{i,n,j}^{end\_restriction} \\ 0, & \text{otherwist} \end{cases} \tag{17}$$

$$\theta_{i,n,j}^{margin} = \frac{\theta_{i,n,j}^{restricted}}{2} \tag{18}$$

$$\theta_{i,n}^{correction} = (\theta_{i,n} - 180) \mod 360 \tag{19}$$

$$\theta_{i,n,j}^{start\_restiction} = (\theta_{i,n}^{correction} - \theta_{i,n,j}^{margin}) \mod 360 \tag{20}$$

$$\theta_{i,n,j}^{end\_restriction} = (\theta_{i,n}^{correction} + \theta_{i,n,j}^{margin}) \mod 360 \tag{21}$$

Where:

| **Variable** | **Meaning** |
|---|---|
| $\theta_{i,n}$ | Flying direction between airport i and n |
| $\theta_{i,n,j}^{start\_restiction}$ | Start of the restriction for route i,n,j |
| $\theta_{i,n,j}^{end\_restriction}$ | End of the restriction for route i,n,j |
| $\theta_{i,n,j}^{restricted}$ | The size of the restricted area for route i,n,j |

The formulas first calculate the size of the margin in 18, which is used to determine the start and end points of the ban. Equation 19 then examines the opposite direction of the first flight, as it is necessary to ensure that the passenger does not travel back along their original route. Once this is established, the start and end points of the ban can be calculated using Equation 20 and 21 by adding and subtracting the margin from the corrected direction of travel of the first flight. Equation 17 first checks whether the start point is smaller than the end point. This is essential because the calculations are based on a circular system; if the value exceeds 360 degrees, the count restarts at 0 degrees. When the end point exceeds 360 degrees, the start and end points must be interpreted differently. Once all this is completed, one can check whether the direction $\theta_{n,j}$ of the potential transfer route falls within the forbidden area. If it does, the variable $Fly_{i,n,j}$ is assigned the value zero; otherwise, it is assigned the value one.

To complete the example illustrated in this Appendix, the following calculations need to be made, as shown below. For the route $Athens \rightarrow Schiphol \rightarrow JFK$, Figure 19 has been created to clarify the calculations.

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow JFK$ **and** $Athens \rightarrow Schiphol \rightarrow Sharjah$

$$\theta_{Athens,Schiphol,Sharjah}^{margin} = \theta_{Athens,Schiphol,JFK}^{margin} = \frac{90}{2} = 45$$

$$\theta_{Athens,Schiphol}^{correction} = 322 - 180 = 142$$

$$\theta_{Athens,Schiphol,Sharjah}^{start\_restiction} = \theta_{Athens,Schiphol,JFK}^{start\_restiction} = 142 - 45 = 97$$

$$\theta_{Athens,Schiphol,Sharjah}^{end\_restriction} = \theta_{Athens,Schiphol,JFK}^{end\_restriction} = 142 + 45 = 187$$

$$Fly_{Athens,Schiphol,JFK} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,JFK} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 1$$

$$Fly_{Athens,Schiphol,Sharjah} = \begin{cases} 1, & \text{if } 97 \leq \theta_{Schiphol,Sharjah} \leq 187 \\ 0, & \text{otherwist} \end{cases} = 0$$

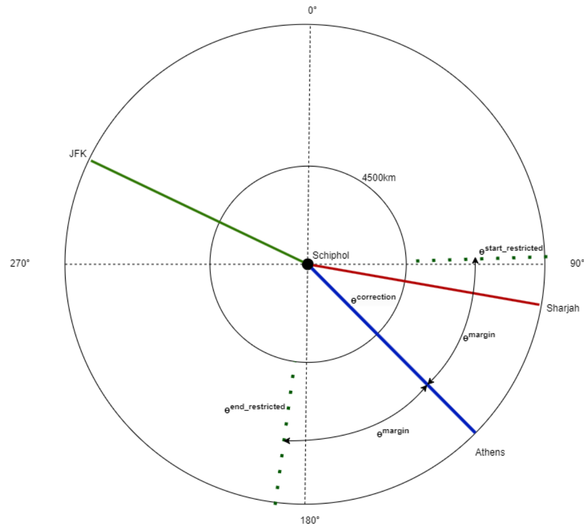


Figure 19: Example illustration if the transfer to the routes $Schiphol \rightarrow JFK$ and $Schiphol \rightarrow Sharjah$ is possible

**Dynamic restricted area calculations for** $Athens \rightarrow Schiphol \rightarrow Heathrow$

$$\theta^{half\_restricted}_{Athens,Schiphol,Heathrow} = \frac{0}{2} = 0$$

$$\theta^{correction\_angle}_{Athens,Schiphol} = 322 - 180 = 142$$

$$\theta^{start\_restiction}_{Athens,Schiphol,Heathrow} = 142 - 0 = 142$$

$$\theta^{end\_restriction}_{Athens,Schiphol,Heathrow} = 142 + 0 = 142$$

$$Fly_{Athens,Schiphol,Heathrow} = \begin{cases} \mathbf{1}, & \text{if } 142 \leq \theta_{Schiphol,Heathrow} \leq 142 \\ 0, & \text{otherwist} \end{cases} = 1$$

Finally, if the calculations for the Dynamic Restricted Area are complete, it means that a passenger arriving from Athens and wishing to transfer at Schiphol would logically transfer to London Heathrow or JFK. A transfer to Sharjah does not make sense and will therefore not be possible.

# Appendix C Information about the case study

This appendix is about the case study performed in the validation and verification section. In the appendix different information about the case study will be given.
The case study is designed to be completely identical to the main study. This means that all steps and parameters are the same, with the only difference being the input data. A small selection of different routes has been incorporated into the system, as detailed in Table 15. The choice of routes is based on the premise that various aspects can be investigated and tested. For instance, routes to Istanbul and London have been included, as well as routes to more remote areas of Europe. As shown in the table, the centre of the routes is at Schiphol and Frankfurt. This allows for a close examination of the reactions of hubs when processing the algorithm. Routes to countries outside the EU have also been added to assess whether passengers can utilise the hub and spoke network.

Table 15: Arrival and Departure Airports in the small model used to validate the algoritme

| **Departure Airport** | **Arrival Airport** |
|---|---|
| AMSTERDAM/SCHIPHOL airport | ABU DHABI INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | BARCELONA/EL PRAT airport |
| AMSTERDAM/SCHIPHOL airport | BOLOGNA/BORGO PANIGALE airport |
| AMSTERDAM/SCHIPHOL airport | BRUSSELS airport |
| AMSTERDAM/SCHIPHOL airport | BUDAPEST/LISZT FERENC INTERNATIONAL airport |
| AMSTERDAM/SCHIPHOL airport | DUBLIN airport |
| AMSTERDAM/SCHIPHOL airport | FRANKFURT/MAIN airport |
| AMSTERDAM/SCHIPHOL airport | KOBENHAVN/KASTRUP airport |
| AMSTERDAM/SCHIPHOL airport | LONDON GATWICK airport |
| AMSTERDAM/SCHIPHOL airport | LONDON HEATHROW airport |
| AMSTERDAM/SCHIPHOL airport | LONDON/CITY airport |
| AMSTERDAM/SCHIPHOL airport | LUXEMBOURG airport |
| AMSTERDAM/SCHIPHOL airport | NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. airport |
| AMSTERDAM/SCHIPHOL airport | PARIS-CHARLES DE GAULLE airport |
| AMSTERDAM/SCHIPHOL airport | ROMA/FIUMICINO airport |
| AMSTERDAM/SCHIPHOL airport | SINGAPORE/CHANGI airport |
| AMSTERDAM/SCHIPHOL airport | STOCKHOLM/ARLANDA airport |
| AMSTERDAM/SCHIPHOL airport | VALENCIA airport |
| AMSTERDAM/SCHIPHOL airport | VENEZIA/TESSERA airport |
| BARCELONA/EL PRAT airport | LONDON GATWICK airport |
| BARCELONA/EL PRAT airport | LONDON HEATHROW airport |
| BARCELONA/EL PRAT airport | PARIS-CHARLES DE GAULLE airport |
| BARCELONA/EL PRAT airport | ROMA/FIUMICINO airport |
| BRUSSELS airport | ABU DHABI INTERNATIONAL airport |
| BRUSSELS airport | ATHINAI/ELEFTHERIOS VENIZELOS airport |
| BRUSSELS airport | DUBLIN airport |
| BRUSSELS airport | ISTANBUL/SABIHA GOKCEN airport |
| BRUSSELS airport | OSLO/GARDERMOEN airport |
| DUBLIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | BOLOGNA/BORGO PANIGALE airport |
| FRANKFURT/MAIN airport | DUBLIN airport |
| FRANKFURT/MAIN airport | ISTANBUL/SABIHA GOKCEN airport |
| FRANKFURT/MAIN airport | LONDON GATWICK airport |
| FRANKFURT/MAIN airport | LONDON HEATHROW airport |
| FRANKFURT/MAIN airport | LONDON/CITY airport |
| FRANKFURT/MAIN airport | ROMA/FIUMICINO airport |
| FRANKFURT/MAIN airport | TRIESTE/RONCHI DEI LEGIONARI airport |
| FRANKFURT/MAIN airport | VENEZIA/TESSERA airport |
| FRANKFURT/MAIN airport | VERONA/VILLAFRANCA airport |
| ISTANBUL/SABIHA GOKCEN airport | ABU DHABI INTERNATIONAL airport |
| MUENCHEN airport | AMSTERDAM/SCHIPHOL airport |
| MUENCHEN airport | NAPOLI/CAPODICHINO airport |
| MUENCHEN airport | PARIS-CHARLES DE GAULLE airport |
| MUENCHEN airport | RIGA airport |
| MUENCHEN airport | SINGAPORE/CHANGI airport |
| MUENCHEN airport | WIEN-SCHWECHAT airport |
| NEW YORK/JOHN F. KENNEDY INTERNATIONAL, NY. Airport | LONDON HEATHROW airport |
| ROMA/FIUMICINO airport | DUBLIN airport |
| ROMA/FIUMICINO airport | ISTANBUL/SABIHA GOKCEN airport |