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Bachelor Thesis

Hayk Gregorian

Air Transport versus High-Speed Rail: From Physics to Economics

Faculty of Engineering and Computer Science
Department of Automotive and Aeronautical Engineering

Hayk Gregorian

Air Transport versus High-Speed Rail: From Physics to Economics

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First examiner, supervisor:	Prof. Dr.-Ing. Dieter Scholz, MSME
Second examiner:	Prof. Dr.-Ing. Martin Wagner

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Aeronautics, Airplanes, Air traffic control, High speed trains, Physics, Energy consumption, Environmental impact analysis, Infrastructure (Economics), Investments, Marketing, Transportation -- Passenger traffic, Choice of transportation, Economics

Abstract

Purpose – This bachelor thesis compares high-speed rail (HSR) transport with air transport. The investigation considers physical fundamentals, energy consumption, environmental impact, infrastructure and investment, market situations, passenger's selection criteria to choose transportation options, and overall economics. ---
Methodology – The thesis combines an investigation of physical principles with a literature review. ---
Findings – Steel wheels on steel rails show by far less rolling resistance to support the train's weight than drag due to lift (induced drag) to support the aircraft's weight. This leads to less energy consumption. HSR trains use electricity from an overhead line. Hence, the environ-mental impact of HSR also depends much on how the electricity is produced. Airplanes only need an air traffic control environment to connect airports. In contrast, HSR needs infrastructure to connect stations. The amount of necessary infrastructure depends on the geological conditions. For example, crossing mountains means high investment. Longer passages over water are infeasible for HSR. High-speed rail is superior to air transport when connecting megacities because the trains have higher transport capacity, offer higher service frequencies and mission reliability, shorter total travel time, shorter access time to stations, shorter unproductive waiting time in stations and potentially lower travel costs. HSR is a strong competitor to airline services and has replaced some short range flights. A comparison of HSR in different world regions shows differences in the market situation and in passenger's selection criteria for transportation options. ---
Research limitations – The potential of high-speed rail was investigated mainly on busy routes with high service frequencies. A comprehensive network comparison between high-speed trains and airplanes was not done and could lead to somewhat different results. ---
Practical implications – The report tries to contribute arguments to the discussion about alternatives to air travel. ---
Social implications – With more knowledge people can make an educated choice between transport options, can vote with their feet, and can take a firm position in the public discussion. ---
Originality/value – A general comparison of HSR and air transport from physical fundamentals to economics seemed to be missing.

Name des Studierenden

Hayk Gregorian

Thema der Bachelorarbeit

Luftverkehr verglichen mit Hochgeschwindigkeitszügen: Von der Physik zur Ökonomie

Stichworte (GND)

Luftfahrt, Luftverkehr, Hochgeschwindigkeitszug, Flugmechanik, Energieverbrauch, Umweltbelastung, Infrastruktur, Investition, Reisemarkt, Passagier, Verkehrsmittelwahl Wirtschaftswissenschaften

Kurzreferat

Zweck – Diese Bachelorarbeit vergleicht den Verkehr mit Hochgeschwindigkeitszügen mit dem Luftverkehr. Bei der Untersuchung wurden die physikalischen Grundlagen, der Energieverbrauch, die Auswirkungen auf die Umwelt, die Infrastruktur und Investitionen, die Marktsituation, die Auswahlkriterien der Passagiere zur Wahl der besten Transportmöglichkeit sowie die Wirtschaftlichkeit berücksichtigt. ---
Methodik – Die Arbeit kombiniert die Untersuchung physikalischer Prinzipien mit einer Literaturrecherche. ---
Ergebnisse – Stahlfelgen auf Stahlschienen weisen einen weitaus geringeren Rollwiderstand auf (um das Gewicht des Zuges zu tragen), als es der Widerstand aufgrund von Auftrieb (induzierter Widerstand) ist, mit dem das Gewicht eines Flugzeugs getragen wird. Dies führt zu einem geringeren Energieverbrauch. HSR-Züge verbrauchen Strom aus einer Oberleitung. Daher hängt die Umweltwirkung von HSR auch stark von der Art der Stromerzeugung ab. Flugzeuge benötigen nur eine Flugsicherungsumgebung, um Flughäfen miteinander zu verbinden. Im Gegensatz dazu benötigt HSR eine Infrastruktur, um Bahnhöfe miteinander zu verbinden. Die notwendige Infrastruktur hängt von den geologischen Bedingungen ab. Zum Beispiel erfordert das Überqueren von Bergen hohe Investitionen. Längere Strecken über Wasser können mit HSR nicht überbrückt werden. Der Hochgeschwindigkeitszug ist dem Luftverkehr beim Verbinden von Megacities überlegen, da die Züge eine höhere Transportkapazität bieten, häufiger verkehren und das Ziel mit hoher Zuverlässigkeit pünktlich erreichen. Die Gesamtfahrzeit ist kürzer. Bahnhöfe liegen verkehrsgünstig und können schneller erreicht werden als Flughäfen. Die Wartezeiten im Bahnhof sind ebenfalls kürzer als am Flughafen. Die Reisekosten sind tendenziell geringer. HSR ist damit ein starker Konkurrent für Fluglinien und hat bereits einige Kurzstreckenflüge ersetzt. Ein Vergleich von HSR in verschiedenen Weltregionen zeigt Unterschiede in der Marktsituation und in den Auswahlkriterien der Passagiere zur Wahl der besten Transportmöglichkeit. ---
Grenzen der Forschung – Das Potenzial der Hochgeschwindigkeitszüge wurde hauptsächlich auf stark befahrenen Strecken mit hohen Betriebsfrequenzen untersucht. Ein umfassender Vergleich im ganzen Streckennetz zwischen Hochgeschwindigkeitszügen und Flugzeugen wurde nicht durchgeführt und könnte auch zu etwas anderen Ergebnissen führen. ---
Bedeutung für die Praxis – Der Bericht versucht, Argumente zu liefern für eine Diskussion über Alternativen zum Flugverkehr. ---
Soziale Bedeutung – Mit mehr Wissen können Passagiere die Auswahl einer Transportoption faktenbasiert treffen, mit den Füßen abstimmen und einen Standpunkt in der öffentlichen Diskussion vertreten. ---
Originalität / Wert – Ein allgemeiner Vergleich von HSR und Luftverkehr mit einer Betrachtung von physischen Grunddaten bis hin zur Wirtschaftlichkeit schien zu fehlen.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Air Transport versus High-Speed Rail: From Physics to Economics

Task for a *Bachelor Thesis*

Background

Passenger air transport uses passenger aircraft to connect airports via airways. Aircraft burn kerosene in gas turbines. High-speed rail (HSR) is a form of rail-bound mobility with a speed of more than 250 km/h. Most high-speed trains are electrically powered via an overhead line. The electricity may come from dedicated power plants. Power plants may use different forms of energy. HSR has been expanded significantly in past decades, especially in China. An increasing number of travelers favor to journey using HSR over air transport on certain routes because of shorter total travel time, shorter access time to station, shorter unproductive waiting time in station, lower travel expenses, higher service frequencies, and more space and comfort in the train compared to the aircraft. Accordingly, air transport lost already some market share to HSR services in certain cases. The situation is different in each country so that regional peculiarities need to be addressed.

Task

Compare air transport with high-speed rail. Start with a literature review. In your further investigation consider:

- physical fundamentals,
- energy consumption,
- environmental impact,
- infrastructure and investment,
- market situations,
- passenger's selection criteria to choose transportation options,
- overall economics.

The report has to be written in English based on German or international standards on report writing.

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List of Symbols

A	aspect ratio
C	coefficient
D	drag
e	oswald factor
F	force
g	gravitational pull
L	lift
m	mass
M	friction moment
r	radius
S	wing area
T	thrust
V	velocity
W	weight
x	distance to point of attack

Greek Symbols

π	pi
ρ	density

Indices

A	acceleration
Air	air
B	bearing
C	curvature
D	drag
GR	gravity
i	induced
I	impulse
L	lift
max	maximum
R	rolling resistance
S	slope

T	traction
WR	wheel resistance
0	zero-lift

List of Abbreviations

AC	Alternating current
CAHSR	California High Speed Rail
CO_2	Carbon dioxide
EC	European Commission
EU	European Union
GHG	Greenhouse gas
HSR	High Speed Rail
HST	High Speed Train
HSL	High Speed Line
ICE	Intercity Express
ISA	International Standard Atmosphere
KTX	Korean Train eXpress
NO_x	Nitrogen oxide
NYC	New York City
OTP	On-time performance
PMT	passenger-miles traveled
SO_2	Sulphur dioxide
TGV	Train à Grande Vitesse (high-speed train)
THSR	Taiwan High-Speed Rail
UIC	International Union of Railways (Union Internationale des Chemins de fer)

List of Definitions

High-Speed Rail
High Speed Rail is a grounded, guided and low grip transport system. (**Leboeuf 2018**, pp. 5)

Air Transport
A transportation system for moving passengers or goods by air.

Rolling Stock
Generalisation of trainsets. (**Leboeuf 2018**, pp. 5)

Rail Vehicle
A vehicle used for the carrying of cargo or passengers on a rail transport systems.

Wheel-Rail-System
Wheel and rail are the fundamental elements of every rail vehicle. The interaction of both constitutes the wheel/rail system, which has the primarily functions of load-bearing, guiding, traction and breaking. (**Knothe 2003**, pp. 1)

Induced drag
Induced drag is drag due to lift, it is an aerodynamic drag that occurs when an object in motion redirects airflow.

Interoperabililty
Interoperabililty describes the ability of multiple systems to interact with each other without the need of modification.

Rolling resistance
Rolling resistance, also called rolling friction, is a type of resistance that occurs when a body rolls over a surface.

Electromagnetic
The generation of a magnetic field by a current in a loop of conductor. (**Ehsani 2013**, pp. 753)

Permanent magnet
A permanent magnet is the source of a magnetic field, without the need of an electric current to generate the magnetic field. (**Ehsani 2013**, pp. 753)

Superconductor
A superconductor is a material that loses its electrical resistance when cooled below the transition temperature. (**Ehsani 2013**, pp. 753)

1 Introduction

1.1 Motivation

Air transport plays a crucial role to cover long distances and for connecting remote areas to the rest of the world (**Bråthen 2011**, pp. 6). Over the past decades, with the introduction of low-cost carriers, short- and medium-haul routes have been made accessible for low ticket prices, consequently winning considerable market shares over full service carriers. At the same time a new generation of railway systems has evolved and matured, continuously generating impact on the global transportation sector: the high-speed rail (HSR).

Unlike air transport, HSR systems are less widespread and therefore less known to the general public, despite its commercial success in various countries. Witnessing the huge success of the Japanese Shinkansen, a network of high-speed railway lines, France soon also introduced its version of the technology in Europe in form of the well-known Train a Grande Vitesse (TGV). In 1981 the French national railway company was already operating several trains at a maximum speed of 270 km/h (**Takagi 2005**, pp. 4). Shortly after, the high speed rail systems were also implemented in Germany and Italy. The high speed railway system started to expand across Europe, also by upgrading the existing rail network infrastructure to support the new high speed train system. Recently, HSR services have gained further momentum, when China expanded the scale of its nation-wide HSR project: More than 20.000 km of new high speed lines are being implemented and over 1.200 trainsets acquired, taking the global lead (**Leboeuf 2018**, pp. 7).

HSR networks have become a threat to air transport, not only due to the recent developments described above, but due to advantages such as higher quality of service, fast loading and unloading times, easier accessibility and higher service frequencies (**Dobruszkes 2014**, pp. 463-464). In some cases, airlines were even forced to withdraw their services from certain regions where an HSR network started its operation: Such as in China, where just a few months after the launch of the high speed train systems between Zhengzhou to Xian and Wuhan to Nanjing, airlines withdrew their operations (**Bullock 2012**, pp. 6, Figure 3).

From the perspective of a passenger, the easily accessible transport options that arise from HSR networks result in various new forms of opportunities. The time savings due to less time being spent on transport itself may result in more jobs becoming accessible to citizens residing further away from business areas, being advantageous for both employers and employees (**Gutierrez 2001**, pp. 241; **Heuermann 2018**, pp. 31). Implementing new and efficient modes of travel can therefore lead to macroeconomic benefits.

While air transport and HSR both represent fast means of travel for short to medium haul routes, HSR systems are electrically powered and therefore, compared to airplanes, do not cause as much direct air pollution.

Although the damage done to the environment is not being eliminated, but just internalized in the electricity generation sector of the economy, many still see tremendous benefits due to the proven reduction of CO_2 emissions (**JTRC 2009**, pp. 12). The possible reduction of traffic congestion is also another significant benefit when introducing high-speed lines. Since some high-speed rail routes have demonstrated to significantly decrease air-lines' market shares, HSR has become an appealing topic for researchers, who are involved in climate change mitigation and consequently in policies leading to less usage of nonrenewable fuel sources (**Dobruszkes 2014**, pp.1). In 2011 the European Union specified in their White Paper the following goals on transport:

> *''By 2050, complete a European high-speed rail network. Triple the length of the existing high-speed rail network by 2030 and maintain a dense railway network in all Member States. By 2050 the majority of medium-distance passenger transport should go by rail.'' (**EC 2011**, pp. 9, 2.5 4.)*

HSR reaches velocities up to 320 kilometers per hour on some routes and thus offers a quick way to access large cities without having to transfer from rural areas. Almost 30.000 kilometers of high speed lines worldwide were in operation at the beginning of 2015 (**UIC 2015**, pp. 5). With faster loading and unloading times and less travel costs than other modes of transport, HSR systems are becoming a more attractive and favored means of travel for businesses and leisure travelers.

1.2 Title Terminology

High Speed Rail

The term *High Speed Rail (HSR)* is, for example by the **International Union of Rails** (**Leboeuf 2018**, pp. 4), defined as follows:

> *HSR is still a grounded, guided and low grip transport system: it could be considered to be a railway subsystem. The most important change comes from the speed. As travel times had to be reduced for commercial purposes, speed emerged as the main factor. HSR means a jump in commercial speed and this is why UIC considers a commercial speed of 250 km/h to be the principal criterion for the definition of HSR.*

Commonly known, *High-Speed Rail* is a form of freight or passenger transport, operating at notably higher velocities than traditional railway vehicles that are guided over dedicated tracks. Although there is no standard, which can be applied on a global scale, the UIC describes a secondary criterion, coherent with the definition of *High-Speed Rail* given by 96/48/EC European directive, where it may not be relevant to run at 250 km/h, since under circumstances the velocity can be enough to catch as many market shares as a collective mode of transport can do:

> *For such speeds above 200 km/h, the infrastructure can be categorized in "High-Speed" if the system in operations complies with:*
>
> - *track equipment*
> - *rolling stock (generalization of trainsets)*
> - *signaling systems (abandonment of trackside signals)*
> - *operations (long-range control centres)*
> - *the geographical or temporal separation of freight and passenger traffics*
> - *and more globally with the standards for High Speed*

Air Transport

The term Air Transport refers to the transportation of freight or passengers, operating with a vehicle, commonly known as aircraft or airplane, which is certified as airworthy by a competent aeronautical authority. The operation of transport is usually carried out by vehicles of static or dynamic aviation properties. In the context of this thesis, air transport refers to fixed-wing aircrafts.

1.3 Objectives

A first sighting of the existing literature in the field of HSR and air transport revealed an incomplete and partially inconsistent view on the impact of HSR on the air transport sector. Therefore, this thesis aims to clarify in which markets the competition between the two modes, HSR and air transport, is primarily taking place, in order to further focus on the more general effects of the implementation of HSR.

The goal is to create a holistic view of the differences as well as strengths and weaknesses of HSR and air transport by comparing these types on a global scale and from different perspectives. Comparison criteria therefore shall include (1) differences in physical properties and behavior, (2) environmental impacts, (3) infrastructural aspects and (4) passengers' modal choices. Moreover, countries taken into consideration are China, Japan, France, Spain, Germany and the United States.

From a physics point of view, operation efficiency shall be analyzed and compared. This is necessary to determine the different fundamental physical advantages of the different forms of transport over each other.

Since the environmental impact of the transportation sector is becoming more of a concern in recent socio-economic and political discussions, this subject shall be part of the analysis. The results of the evaluation of the energy efficiency of HSR networks and aircrafts are to be used as an indicator for sustainability. General comparisons of pollutants are to be drawn and evaluated in their extent of harmfulness to the environment.

The infrastructural aspects of each mode shall be compared, also with respective to their costs of implementation. Since HSR systems are less common as transportation means, a strong focus shall be set on HSR networks in terms of investments and requirements for the installation of high-speed rail systems.

Potentials for the introduction of Maglev technologies are to be investigated to draw conclusions for an outlook for the future. For this, the technology will be introduced and current states of the ground based transportation mode, using magnetic levitation is to be evaluated.

Criteria for the selection of a mode of transport by passengers shall be researched and evaluated in order to conduct a relevant comparison of HSR and air transport in this field.

Conclusively, results are to be brought together for a general evaluation of the competitiveness of HSR in comparison with air transport.

1.4 Literature Review

In order to create an overview of the existing literature dealing with HSR and air transportation a literature review has been conducted. Various publicly available web sources of scientific literature, such as Science Direct, Springer Link or Google Scholar, have been searched for combinations and derivations of keywords such as “HSR”, “high speed transport”, “air transport”, “competition”. In addition a “backward referencing search” was conducted by scanning the literature references of matching authors. Moreover, other literature of prominent authors in the field was searched (“forward search”). The decision whether to include a literature resource in this thesis was primarily based on the title, abstract or executive summary of the literature.

Much of the discovered literature discussed only limited aspects of HSR or air transportation and even a lesser portion of the literature directly compared HSR and air transportation. Those pieces of literature that compared both forms of transportation, however, often only discussed them on a local level, e.g. the Chinese market or the French market or only on a partially global scale. Therefore, this thesis tried to combine the results of this literature with the aim to make a comparison of these forms of transportation on a global scale.

Among other literature that is quoted throughout this thesis and mentioned in this thesis’ literature references, the following literatures are notable for containing valuable insights into the subject of HSR and paving the way for a deeper comparison with air transportation:

The *International Union of Railways* offers general information on the operation HSR networks, for example in form of brochures and publications (**Leboeuf 2018**), and provides definitions of the system. Starting with the development since the introduction of the Japanese Shinkansen, **Leboeuf 2018** shows the growth of high-speed train systems up to present time on a global scale. Apart from technical specifications, the UIC also presents requirements for the construction of the infrastructure and its maintenance. Comparisons of other modes of transport in terms of travel times, travel expenses and environmental issues are also drawn on the basis of the data provided by several operators. **Leboeuf 2018** states that HSR is most attractive to passengers, compared to air travel, when traveling over distances between 300 – 600 km (**Leboeuf 2018**, pp. 19). The UIC also concludes on the basis of a survey conducted in Europe, that the criteria for the selection of a mode of transport is mainly dependent on travel expenses, the total travel duration, service frequencies and reliability.

Albalate 2010 researched HSR projects on an international scale. The majority of the review sets its focus on countries where the introduction of the lines has resulted in notable success. For this, the Shinkansen in Japan, the TGV in France, the ICE in Germany and the AVE in Spain were researched and compared. In the review, costs for the construction and operation of HSR networks are listed for some routes, showing significant differences between the four European countries, although no further information for the reasons of dissimilar costs is offered.

Albalate 2010 states that modal shifts could be observed after the introduction of HSR. Similar to **Givoni 2006** (see further below), air services losing market shares to high-speed rail in France and Spain were most apparent, especially between Barcelona and Madrid, where HSR gained a third of airlines market shares (**Albalate 2010**, pp. 23).

In terms of economic impacts, he states that large cities might gain limited benefits, while cities located between notes connected through HSR lines suffer an overall negative impact due to economic activities being drained away (**Albalate 2010**, pp. 25).

Albalate 2010 also concludes that high-speed rail is more environmentally efficient than air transportation or road travel by private car, although the CO_2 footprint is higher than that of conventional intercity trains. Because of that, he claims that HSR is not a “useful tool” to reduce CO_2 emissions (**Albalate 2010**, pp. 26). He also points out that the overall impact of HSTs on energy consumption, and therefore the environmental impact, is highly dependent on the source of its passengers, weather newly generated or attracted from other existing types of transportation (**Albalate 2010**, pp. 24).

Campos 2009’s research is based on data from 20 countries where HSR networks are already in operation, are being constructed or are still in the planning phase. He starts by describing the *exploitation models* to point out dissimilarities when introducing HSR infrastructure on an international scale.

Campos 2009 analyzed economic costs of HSR projects. After investigating the Shinkansen in Japan between 1964 and 2005, which operated over 150 billion passenger-kilometers and the Korean lines which recorded over 40 million passengers per year in the first years of operation, they conclude that there clearly is a high demand for HSR systems. **Campos 2009** also states that the European HSR networks reached 76 billion passenger-kilometers in 2005 alone (**Campos 2009**, pp. 26).

Campos 2009 concludes, that apart from other demand driving factors like ticket fares, service quality and passengers income, the rapid growth has also been due to the progress in building HSR infrastructure (**Campos 2009**, pp. 26). Furthermore, **Campos 2009** states that after HSR demand starts growing rapidly, with observable shifts in market shares from other modes of transport and through own demand generation, the growth rate declines. This was based on the Japanese Shinkansen lines, where in the first 20 years about 100 billion passenger-km were gained. Compared with the next 20 year-interval, where only a 50 billion increase in additional passenger-km was achieved (**Campos 2009**, pp. 26). For this hypothesis, no other evidence is available, due to Japan’s long history of implementing high-speed rail networks.

Due to fragmented information of the used database, **Campos 2009** does not offer information regarding environmental issues of HSR, although he states that they are not negligible.

Givoni 2006 first approaches the case of HSR networks by describing technological standards and the main models used in different countries, following up with the development of these systems, mainly in Japan, France and Spain.

His review focuses then mainly on economic costs and benefits in these countries, where he researches the attraction of HSR for passengers of different types of transportation, especially from air travel. Based on data from the French TGV line connecting Paris to Lyon between 1981 to 1984 and the line connecting Madrid with Sevilla from 1991 to 1994, he shows that the introduction of the TGV resulted in a 24 % loss of market shares for airlines, similar to Spain, where 27 % market shares were lost (**Givoni 2006**, pp. 601, Table 1).

He states that shorter travel times, higher service frequencies and lower costs lead to changes in the modal share, and investigates how these improvements are achieved. **Givoni 2006** concludes that the reduction in travel times is not only dependent on high operation speeds but also on the amount of stations HSR services.

In terms of the environmental impact of the mode, he concludes that HSR, although effecting local air pollution, causing noise nuisance and consuming land, holds significant potential to reduce the amount of pollution it causes if renewable and nuclear sources are used to generate electricity.

1.5 Structure

The first sections of this chapter have already discussed the motivation as well as the goals and objectives of this thesis and addressed some of the key definitions relevant for this thesis. In this section, the further structure of this thesis is presented and explained.

The comparison between HSR and air transport is partitioned into four main chapters. Each chapter represents one of four different comparison criteria: (1) Differences in physical properties and behavior, (2) environmental impacts, (3) infrastructural aspects and (4) passengers' modal choices.

In the first chapter of this thesis, a comparison of *physical* fundamentals of both high-speed rail vehicles and aircraft is drawn. In this context, the different forces that impact the vehicle during its operation are explained and compared. By doing so, fundamental differences are outlined and highlighted. The chapter is concluded with a comparison of resistance forces including the resulting efficiency levels for both modes of transport.

The next chapter focuses on the *environmental* impact of the two types of transportation. The chapter is divided into two parts. It starts with a comparison with regard to energy efficiency in which the factors *sustainability* and *environmental friendliness* are taken into account. The second half of this chapter is an investigation of the amount of pollution each transportation mode causes in terms of emissions and noise. Here fundamental differences are pointed out and evaluated.

The third chapter compares the *infrastructure* of the air-travel sector with the one of high-speed rail. The focus is put on how HSR and air transport operate their routes and what they need to conduct their transport itineraries. Moreover, the question of infrastructural costs is addressed.

The last chapter of the comparison-series in this thesis focuses on the *modal choice* of passengers. In a first step, the critical determinants for modal choice are researched, mainly using a survey conducted by **Leboeuf 2018**. Consequently, the main determinants for the modal choice of travelers are chosen for comparing HSR and air transport. For this task, 6 typical itineraries are selected, from which travel time data, travel expenses, service frequency and reliability are derived. On this basis, the competitiveness of HSR and air transport is eventually determined.

After having completed the comparison of HSR and air transport, the following chapter closes the main part of this thesis with a discussion on *Maglev*. The goal is to give the reader a broad sense of how this technology relates to HSR and air transport. In order to stay within the scope of this thesis, Maglev will not be fully contrasted with the aspects presented in the previous chapters (such as infrastructure, environmental impact etc.) but only briefly described and sporadically compared to these aspects to give the reader a broad understanding.

Finally, this thesis closes with a summary and a conclusion. In this context, the main findings of this thesis are highlighted, implications are discussed and limitations are stated. A short outlook is given.

2 Physical Principles

This chapter will touch upon the fundamental physical principles of aviation and those of railway vehicles to give a basic understanding of the dynamics of both transportation modes. Since it is not in the spirit of this thesis to investigate advanced physical derivates of both aviation and rail vehicle mechanics, but to give an initial impression of the most important interrelationships of the acting forces, a detailed absorption of the physical background will be avoided.

The fundamentals discussed in the following chapters were mainly taken from **Scholz 2019** and **Torenbeek 2009** *for Flight Mechanics* and from **Ihme 2016** for *Rail Vehicle Mechanics*.

2.1 Flight Mechanics

A steady and balanced equilibrium forms the basis for flight mechanical issues. Therefore the initial assumption of a left and right symmetry of the classical fixed-wing aircraft is essential for the following equations of this chapter. Additionally, instead of looking upon an aircraft moving through a stationary atmosphere, the airplane is considered as a stationary body immersed in the surrounding air, which is moving uniformly and in the opposite direction of the enclosing gases.

Generally aircraft operate by accelerating an amount of surrounding air in a down- and/or backward direction through the production of a lift or thrust force, which is applied in that same direction. Taking Newton's third law of motion into account (action = reaction), an equally distributed force is acting upon the aircraft, being the lift L or the thrust T. For steady flight to be achieved, these forces must at least equal to the weight W of the aircraft (**Torenbeek 2009**, pp. 52). To implement maneuvers, the lifting forces acting upon the lifting surface must be greater or smaller than the weight, allowing the direction of motion to be changed. Consequently, to realize dynamic aviation with fixed-wing aircraft, a continuous and downward flow of air surrounding the aircraft, the downwash, is essential (**Torenbeek 2009**, pp. 52).

A necessity to understanding the mechanics of flight of a classical fixed-wing aircraft is the distribution of forces acting on the body and its surroundings. Figure 2.1 illustrates the equilibrium of the acting forces on an airplane in a steady and straight level flight. In this case, just like the aircraft's plane of symmetry, all the components of the aerodynamic forces coincide with the direction of flight. Because of fuel consumption, in reality the weight and the altitude vary in time. Since this doesn't rapidly change the conditions of the flight, it is referred to as a quasi-steady flight, to which the equilibrium condition still applies.

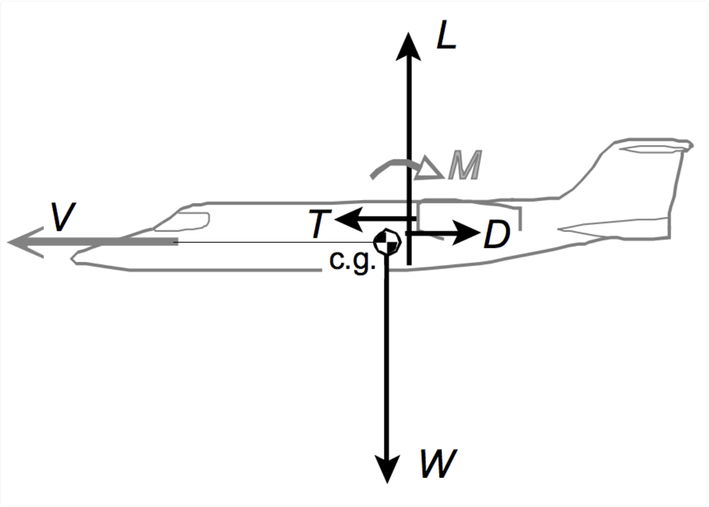

Figure 2.1 Equilibrium of forces in steady level flight (**Torenbeek 2009**, pp. 60)

In this type of flight the forces of lift, thrust, drag and weight all cancel out and the plane flies at a constant velocity. The equilibrium of forces is therefore described as follows:

$$L - W = 0 \quad \text{and} \qquad T - D = 0 \tag{2.1}$$

With the flight path assumed to be horizontal and thrust acting parallel to the flight direction, the motion is described by the equations

$$L = W \quad \text{and} \quad T = D \tag{2.2}$$

Like every body in motion, an aircraft experiences the force of weight W, caused by the gravitational pull g of the earth on its center of gravity and the mass of the body itself,

$$W = mg \tag{2.3}$$

with the gravitational force directed towards the center of the earth, and for reasons of simplification assumed to be constant and not dependent on the altitude.

The lift L consists of all aerodynamic forces acting on the aircraft when resolved perpendicular to the flight path. It is the force which enables flight. As a result of pressure forces on the surface exposed to the flow, lift or up-lift is created. Although every section of the exposed aircraft is responsible for the generated lift, the wing and tailplane surfaces are the main contributors to the up-lifting effect. The following equation shows the composition of the formula used to describe lift (**Torenbeek 2009**, pp. 58).

$$L = C_L \frac{1}{2} \rho V^2 S \tag{2.4}$$

The wing generates the downwash and results in the lift which largely works on it. Figure 2.2 shows an airfoil with the airflow illustrated as streamlines with arrows around it. The dividing streamline in the middle splits at the leading edge as it hits the stagnation point C. Due to the shape of the airfoil and the angle of attack (measured angle of the wing relative to the airflow), the airspeed above and underneath the airfoil is not the same. For one, the increase in velocity of the airflow above the wing is accompanied by a corresponding decrease in static pressure. The difference in pressure above and below the wing results in an up-lifting effect. Additionally, the air that runs above the wing follows along the shape with its curvature. As it moves past the upper airfoil, it leaves the trailing edge of the wing with a continuous downward direction due to its shape, causing the essential lift-force to act upon the wing.

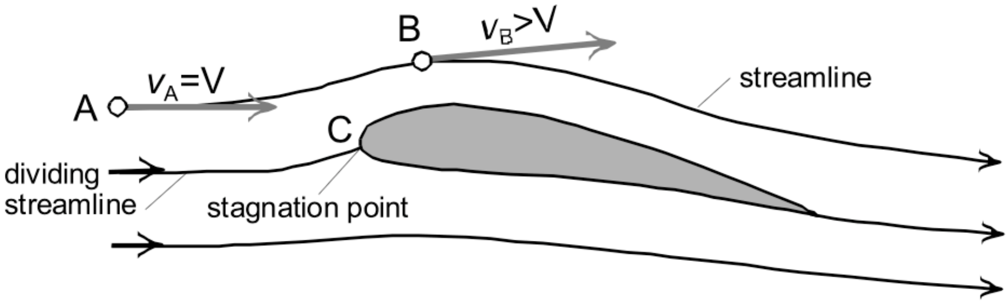

Figure 2.2 Streamlines around an airfoil section (**Torenbeek 2009**, pp. 91)

Looking back upon (2.4), S describes the wing area, measured in the plan view of the aircraft. The altitude determines the air density ρ, for which the International Standard Atmosphere (ISA), a static atmospheric model, is used. Taking temperature, density, pressure and viscosity into account, it describes the earth's atmosphere over a certain range of altitudes. Furthermore, to develop this force, an airspeed V relative to the surrounding air is necessary.

The lift coefficient C_L depends on the incidence angle of the wing relative to the flight path. It is a dimensionless quantity, relating the lift generated by the fluid velocity, a wing area and a lifting body to the fluid density around it. Therefore, using Equation (2.4), the lift coefficient can be described as follows:

$$C_L = \frac{2L}{\rho V^2 S} \tag{2.5}$$

The component sum of all aerodynamic forces acting on an aircraft which work towards the opposite direction of its flight course is called drag and labeled D. Similar to lift, it can be described with the airspeed, the air density and the wing area S, with the only difference of the coefficient used, in this case being the drag coefficient C_D.

$$D = C_D \frac{1}{2} \rho V^2 S \tag{2.6}$$

Drag consists of pressure and frictional resistance acting on the aircraft. Pressure drag is composed of induced and form drag, where induced drag, acting predominantly on the wing and the horizontal tail is a direct consequence of lift generation. This type of drag occurs whenever airflow coming at a moving object is redirected. Within the scope of this paper the focus will be set on the induced and zero-lift drag, which follows further below. With the use of the lift-to-drag ratio or glide ratio, the aerodynamic efficiency can be described.

$$\frac{L}{D} = \frac{C_L}{C_D} \tag{2.7}$$

At its highest value, many important flight performances can be derived from, since the maximum range of an aircraft, at a given airspeed, is proportional to $(L/D)_{\max}$.

Since the lift-force required for the flight is set by the aircraft's weight, a lower drag to the generated lift results generally in a more positive fuel economy of the flight. Figure 2.3 illustrates the maximum lift-to-drag ratio graphically. When drawing a tangential line to the drag polar from the graph's origin, the slope can be used to determine the maximum glide ratio $(L/D)_{\max}$.

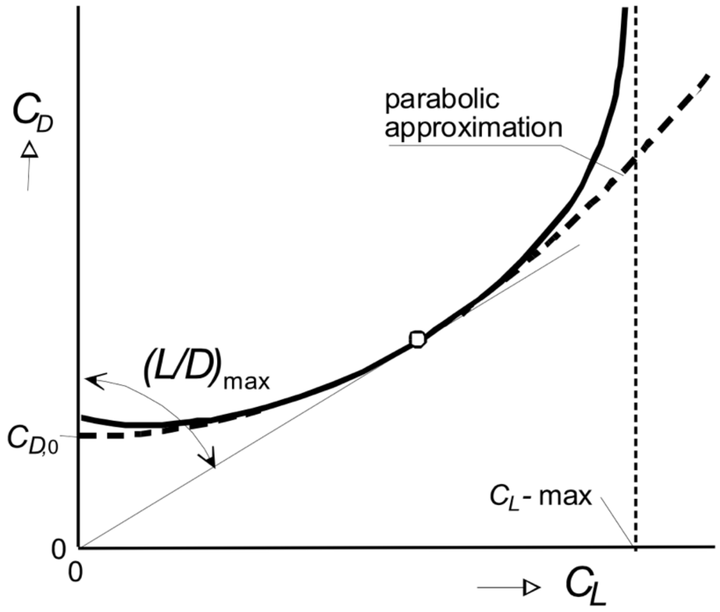

Figure 2.3 Maximum glide ratio (**Torenbeek 2009**, pp. 175)

The zero-lift drag is described as the drag that generates 0 lift, while acting as a resistance force, shown as part of the total drag in (2.8),

$$D = D_0 + D_i \tag{2.8}$$

with the corresponding drag coefficient

$$C_D = C_{D_0} + C_{D_i} \,. \tag{2.9}$$

Using the momentum equation and the derivation by H. Glauert and A. Betz (**Torenbeek 2009**, pp. 167), the induced drag coefficient can be described as

$$C_{D_i} = \frac{C_L^{\,2}}{\pi A e} \,. \tag{2.10}$$

In (2.10), A describes the aspect ratio, it is defined by the square of the wingspan divided by the wing area. The factor e below the fraction line is known as the Oswald factor, which is a dimensionless efficiency factor obtained by plotting values of C_D versus $C_L^{\,2}$. It's typical values lie between 0,65 and 0,90, the ideal value for an elliptical wing is 1,0.

For the parabolic drag polar, the ratio is obtained analytically by the derivative of the glide ratio divided by the lift coefficient equaling zero.

$$\frac{d(C_D / C_L)}{dC_L} = 0 \;\rightarrow\; -\frac{C_{D_0}}{C_L^{\,2}} + \frac{1}{\pi A e} \;\rightarrow\; C_{D_0} = \frac{C_L^{\,2}}{\pi A e} \tag{2.11}$$

At maximum lift-to-drag ratio in horizontal flight, the zero-lift drag and the induced drag are both equal to half of the total drag, as shown in (2.12).

$$C_D = 2C_{D_0} = 2C_{D_i} \tag{2.12}$$

To repeat, this means that in steady flight, when the lowest possible drag-force is acting on the aircraft, the induced drag is 50% of total drag, keeping in mind that induced drag is drag due to lift, which is a direct result of weight.

2.2 Rail Vehicle Mechanics

This chapter will set its focus upon the resilience of rail vehicles to attain a basic comprehension of the forces acting on the moving body. To begin with, a brief explanation of the operating principles is meant to offer a better understanding of this chapter.

Railways are mechanically guided transport structures, which use a wheel track system. Rail vehicles have either their own drive or are pulled or pushed by a locomotive. Nowadays the most common types of locomotives are diesel and electric. Electric locomotives are supplied by additional rails or overhead wires. According to DIN 25003, rail vehicles belong to the track guided vehicles, equipped with a wheel flange and bound to a consistent gauge. The connection between the wheel set and the rail is the essential interface in railway systems (**Janicki 2013**, pp.15). A unique characteristic of vehicles running on railways are its wheels, which are particularly designed for the use on rail tracks and are commonly made of steel. These are either forged or cast and heat-treated to obtain a certain level of hardness.

Since the objective of this thesis is to compare the two modes of transport, a comparable force to the induced drag acting on aircraft should be adduced in high speed rail vehicles. In the case of rail vehicles the main force directly resulting from the weight of the moving body is the rolling resistance. Drawing a comparison between these two forces is therefore a suitable approach to contrast the efficiency of aircraft with that of HSR vehicles.

To enable movement of rail vehicles, following applies:

$$F_T = \sum F_D \tag{2.13}$$

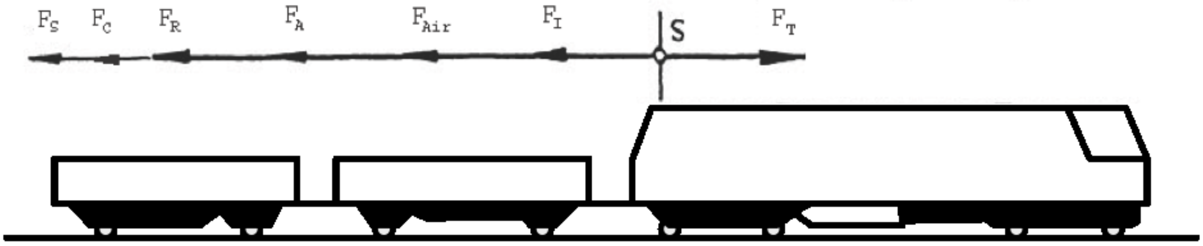

Figure 2.4 Rail vehicle force distribution

F_T describes the traction of the vehicle and F_D is the sum of all drag forces acting on it. The resistance forces taking effect on the moving body consist of acceleration and drive resistance, whereby the latter is calculated by adding the running resistance with those forces which occur due to slopes and curvatures on tracks. Lastly the running resistance is separated into air, shock and rolling resistance.

$$F_T = F_R + F_S + F_C + F_A + F_{Air} + F_I \tag{2.14}$$

F_S and F_C are the forces due to the track, F_A is the acceleration resistance, F_{Air} the resistance due to air, F_R the rolling and F_I the impulse resistance. The forces which are a direct consequence of the weight are for one the rolling resistance, and those which occur when there is a pitch angle (F_S) or a curvature (F_C) along the rail track. Since the vehicle is not constantly affected by a slope or curves, the focus will be set on the rolling resistance F_R. To repeat, drag due to rolling is proportional to the weight of the vehicle:

$$F_R = C_R \cdot m \cdot g \tag{2.15}$$

At the contact surface between wheel and rail elastic deformation occurs. This continuously deforming contact area or flattening of the wheel, whose size is approximately that of a cent coin, moves along the track as the wheels roll over the rails. This process of so called “walking” or “fulling” is the cause of the rolling resistance. Because of the contact area formation of the wheel’s contact surface due to its vertical force distribution, the opposing force caused by the weight operates with the lever x displaced in front of the wheel’s center. With the equilibrium of moments the force for the rolling resistance can be determined (**Ihme 2016**, pp. 35).

$$F_{WR} \cdot r = F_{GR} \cdot x \tag{2.16}$$

Additionally, the friction caused by the axle bearing in the center of the wheel is added to the equation:

$$F_{WR} \cdot r = F_{GR} \cdot x + M_B \tag{2.17}$$

The friction moment of the bearing is the product of the bearing load F_{GR} and its coefficient C_B:

$$M_B = F_{GR} \cdot C_B \tag{2.18}$$

Eventually the drag force of the wheel is determined as follows:

$$F_{WR} = \frac{F_{GR} \cdot x + M_B}{r} = \frac{F_{GR} \cdot x + F_{GR} \cdot C_B}{r} = \frac{x + C_B}{r} F_{GR} = C_R \cdot F_{GR} \tag{2.19}$$

Apart from the combination of materials, in this case being a steel based wheel and a steel based track, the rolling resistance coefficient C_R is determined by the wheels geometry. For rail vehicles the coefficient is about a power of ten smaller than that of typical road vehicles. Mostly it lies between 0,001 and 0,002. A reason for that is the size of the contact surface, which affects the lever x as shown in Figure 2.5. The difference in size of the contact surfaces in wheel-track systems and those of conventional road vehicles on asphalt or concrete can be pictured imagining a 2-cent coin held next to a postcard (**Ihme 2016**, pp. 36).

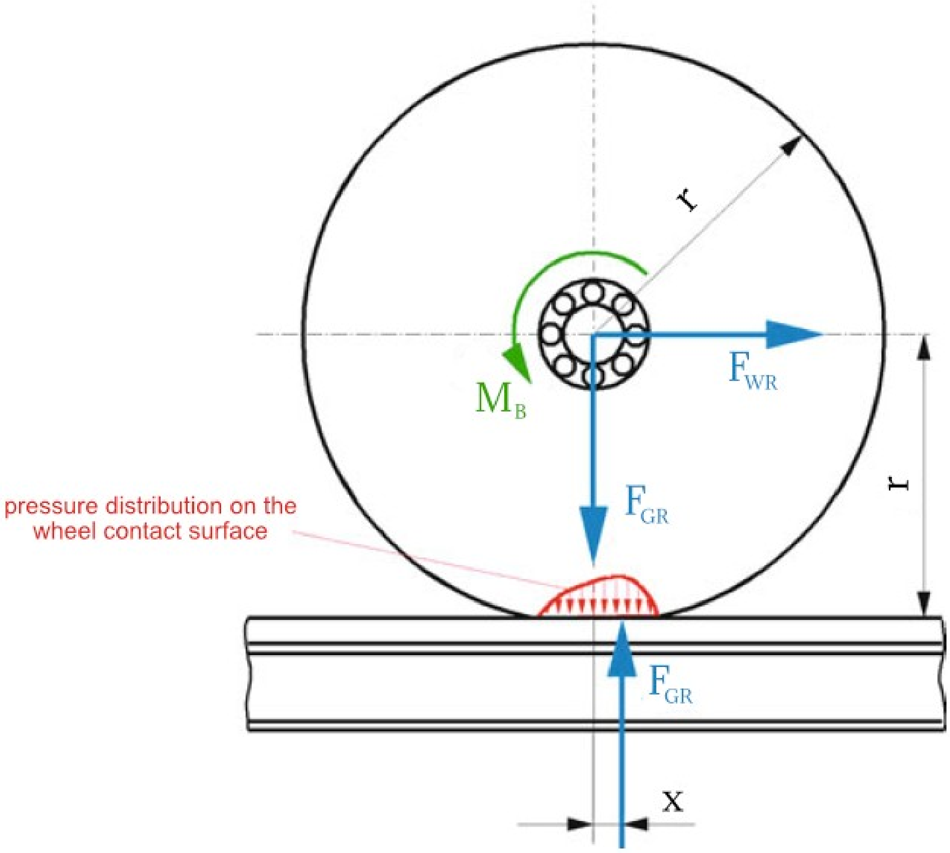

Figure 2.5 Rolling resistance (after **Ihme 2016**, pp. 36)

For that reason the rolling friction in wheel-track systems is rather small due to the hardness and non-deformable structure of the two materials which are in direct contact with each other. The high carrying capacity of steel is consequently the reason for the comparably low rolling drag values between wheel and track, but also reason for the low adhesion and therefore small transmittable drive and brake forces.

Figure 2.6 illustrates the measured drag components of a four-part ICE test train. The test drives were carried out on open track and inside of a tunnel. The air resistance, or aerodynamic drag, predominates the remaining drag forces at unaccelerated level drive for as little as 40 km/h. When driving through a tunnel an associated tunnel resistance is counteracting the driving direction.

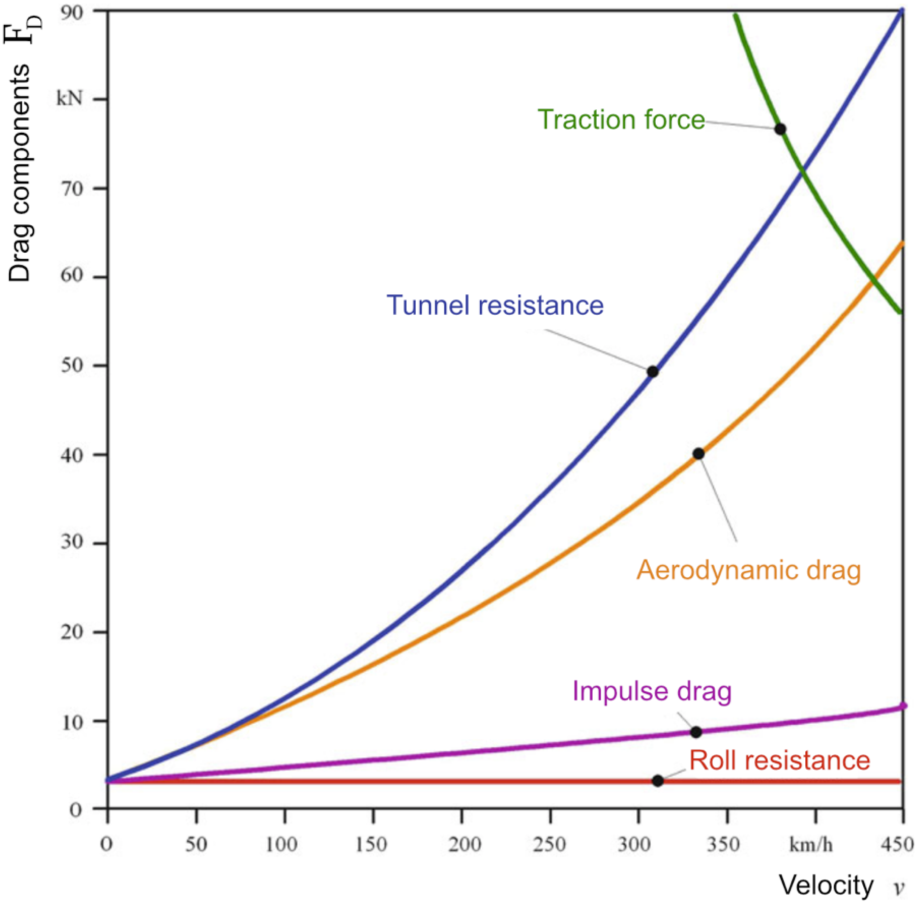

Figure 2.6 ICE test drive through tunnel (after **Ihme 2016**, pp. 42)

The impulse resistance shown as a purple curve is a result of cooling air in- and outtake and can thus be ignored. The graph displays the comparably low resistance resulting from the wheel-track contact, illustrated in red, and staying almost constant over the whole track. When the ICE reaches 300 km/h the aerodynamic drag amounts to $\approx$ 35kN, while rolling resistance stays at $\approx$ 4kN, being approximately 8.5% of total drag which acts on the ICE outside of the tunnel (**Ihme 2016**, pp. 42).

2.3 Comparison of Physical Fundamentals

Assuming rail vehicles with the same payload as aircraft have similar values for D_0, the aerodynamic efficiency or glide ratio E shown in (2.20), which is calculated by dividing lift through drag or the lift coefficient through the drag coefficient, can then be compared by neglecting D_0 from the equation. (2.9) shows the glide ratio which was introduced in the previous chapter.

$$E = \frac{L}{D} = \frac{mg}{D_0 + D_i} \tag{2.20}$$

Now to gain a performance factor which can be compared between both modes, D_0 will be removed, and a new ratio can be introduced.

$$E_i = \frac{L}{D_i} = \frac{mg}{D_i} \tag{2.21}$$

In horizontal flight, D_0 comprises $\frac{1}{2}D$. For aircraft, E_i would then be calculated as follows:

$$E_i = \frac{mg}{\frac{1}{2}D} = 2E \tag{2.22}$$

To obtain comparable values of E_i for rail vehicles, the equivalent of D_i has to be used. In this case D_i is replaced with F_R , the rolling resistance using Equation (2.15).

$$E_i = \frac{mg}{F_R} = \frac{1}{C_R} \tag{2.23}$$

10 is a general value for the glide ratio of a passenger aircraft. Values for E_i would then be doubled, amounting to 20 in the case of aircraft. Rail vehicle would present a far greater factor of about 667, about 10 times higher than of road vehicles, as shown in Table 2.1 below.

Table 2.1 Performance factor comparison

	E	E_i
passenger aircraft	20	40
	C_R	$1/C_R$
rail vehicle	0.0015	667
road vehicle	0.015	67

This comparison shows the high potential of rail vehicles in terms of performance efficiencies in operations, due to the use of steel based wheel-track-systems.

Building on the thought process of **Scholz 2018** (Slide 7), an aircraft is to be placed on railways with a similar wheel-track system used by trains. By doing so, the reduced amount of drag acting on aircraft when operating on tracks can be approximated.

For this, the weight of a train is assumed to be the same as that of an aircraft, and the amount of rolling resistance of a train will be used from Figure 2.6. (2.12) shows that in minimum drag flight the induced drag is 50 % of total drag. Using the 8.5 %, computed from the ICE test drive, rolling resistance of a train is 4.25 % of the total induced drag of an aircraft. Since induced drag is 50 % of the total drag, a reduction of approximately 47.9 % can be reached through the use of tracks.

While the performance of aircraft on tracks might be enhanced through the reduction of resistance forces, lightweight design may still face other challenges on railway systems, for example through cross winds. Therefore, further research should be done to determine if lightweight design truly holds potential for track-based mobility.

Furthermore it can be seen, that aerodynamic drag has the biggest impact on the total resistance acting on vehicles operating on railways. The design of the underbelly i.e. is a significant factor causing a large amount of drag. Through the introduction of fairings under the train, a considerable decrease of overall drag can be achieved (**Ahmed 1985**, Figure 3.1.4).

Either mode of transport presents various advantages and disadvantages which have to be taken into consideration. Nevertheless, through the comparison of drag components assets and drawbacks of each mode of transport can be pointed out on a fundamental basis.

HSR systems benefit from a rather small impact of the weight on overall mobility, while aircraft manufacturers struggle in terms of material use to keep the weight to a minimum, and by doing so the induced drag as low as possible. Lightweight design generally entails a significant amount of costs. On the other hand, costs for the infrastructure of HSR systems are also considerably high as discussed in a later chapter.

3 Environmental Impact

Comparing HSR with the air transport sector in terms of the environmental impact is a critical topic. Usually high-speed rail networks are described as transportation modes with low emission output since they are predominantly electrically powered. Nevertheless, HSR operations contribute negatively to the environment through noise, land take, climate change and local air pollution. In this section the main factors affecting the environment will be pointed out and the extent of the impact both modes of transport bring about will be evaluated.

3.1 Energy Efficiency

To begin with, the energy efficiency will be used as an indicator to determine the potentials of sustainability and the reduction of environmental damage. Yet, comparing different transportation modes based on the efficient use of energy is a complex subject due to initial dissimilarities in operations, manufacturing and required infrastructure.

First the calculation target of the consumed energy of the mode has to be defined. For this, mostly the final energy used by the vehicle engine is compared and the section of the cycle corresponding to the energy extraction and processing is neglected, despite its importance, especially when comparing fundamentally different modes of transport. The same applies to the energy consumed by the infrastructure and maintenance (**Benito 2018**, pp. 13-14).

Another issue is the selection of the efficiency parameter, which can include the transportation subject along a certain distance. Different standards for weights of passengers for example make comparisons more difficult. Additionally, distances traveled with each mode of transport vary due to the infrastructure or unique properties of the vehicles (**Benito 2018**, pp. 13-14).

Figure 3.1 shows an energy efficiency analysis by **Chester 2009**. With the life-cycle analysis methodology, the Californian high-speed rail system (CAHSR) and three commercial aircraft models were compared, using MJ/PMT (Mega Joules per Passenger-Mile Traveled) as the efficiency parameter. The assessment covers vehicle and infrastructure operations, manufacturing, maintenance and insurance and the fuel production.

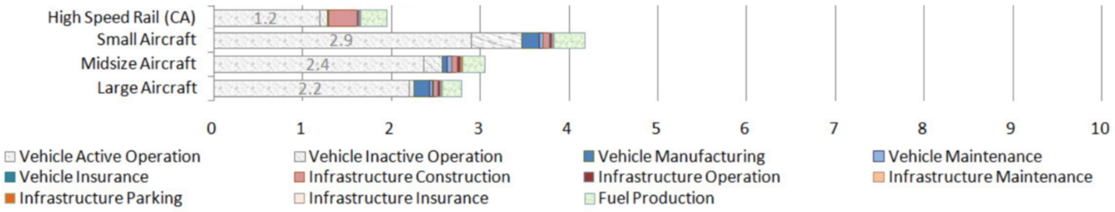

Figure 3.1 Energy efficiency in MJ/PMT (after **Chester 2009**, Figure 1)

The life-cycle analysis by **Chester 2009** as shown above in Figure 3.1 primarily confirms that HSR systems prove to be more efficient in terms of energy consumption. although still a comparably large amount is used for the infrastructure construction, which amounts to about a fifth of the total energy consumed per passenger-mile traveled. Production of fuel makes up a similar amount for each mode, while vehicle operations for aircraft consume the highest amount of energy.

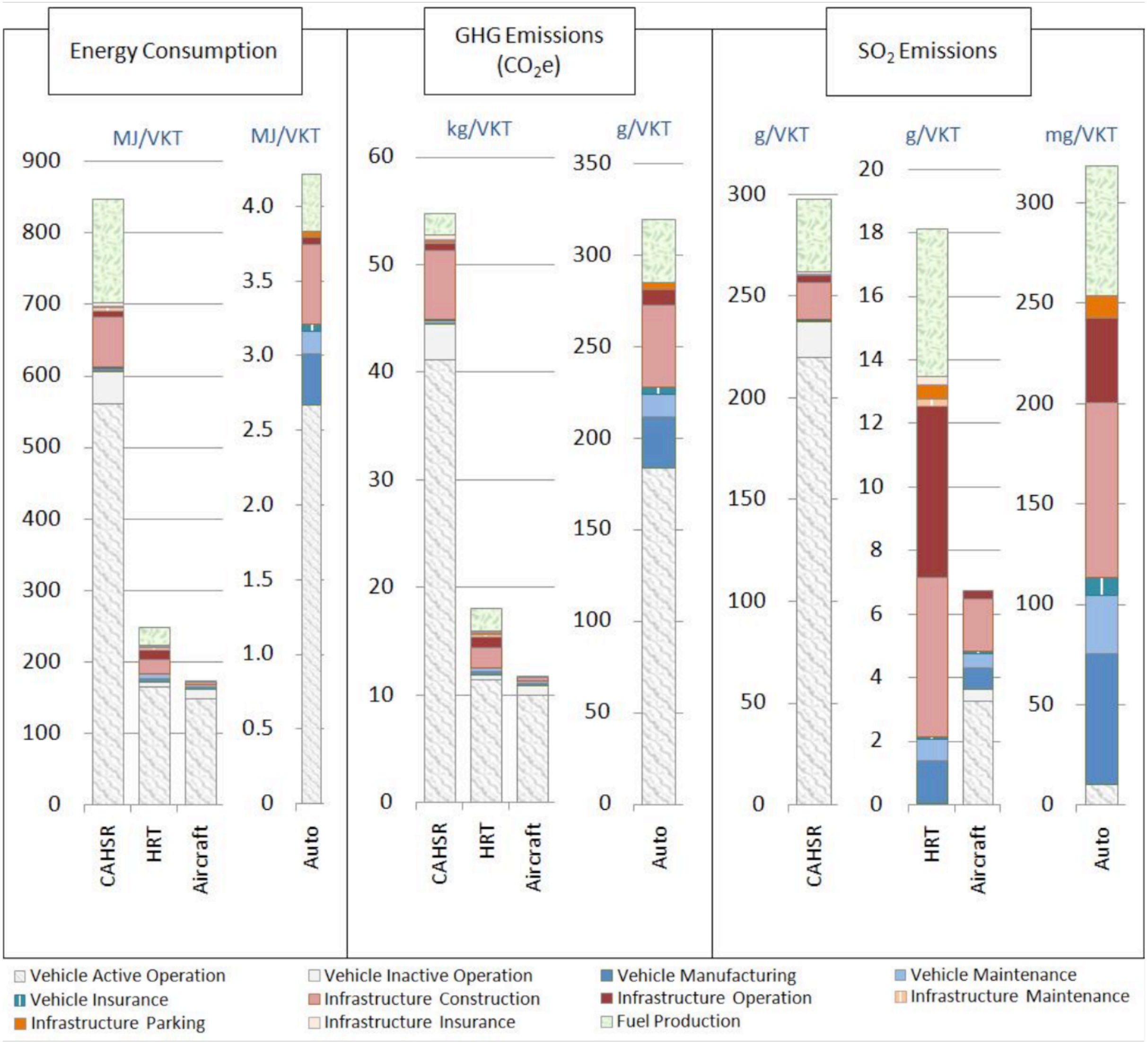

Figure 3.2 Energy consumption, GHG and SO_2 emissions (after **Chester 2010**, pp. S6)

Figure 3.2 displays a life-cycle analysis of **Chester 2010** for the CAHSR compared to aircraft, private cars and heavy-rail transit. On the left the energy consumption in MJ/VKT (Mega Joules per Vehicle-Kilometer Traveled) is shown. The electricity consumption for the CAHSR is based on the German ICE high-speed rail system, which the California High Speed Rail Authority speculates to be similar to the trains proposed for California. According to **Chester 2010**, the CAHSR Authority estimate the energy consumption of the proposed trains at 170 kWh per vehicle-kilometer traveled (**Chester 2010**, pp. S2). The graph shows the significant amount of energy consumed by a vehicle per kilometer, when compared to the other modes. From these values one can conclude, that in case of an unsuccessful introduction of HSR, the energy efficiency would be rather low, due to the high consumption of electricity to operate such large vehicles, without transporting the necessary amount of passengers to function as an energy efficient mode.

3.2 Pollution

The release of carbon dioxide is commonly known to harm the environment, since it is considered a greenhouse gas (GHG) which causes global warming and consequently climate change. The extraction of oil is therefore directly related to the emission of CO_2, since oil is largely used to produce fuel, which is then burned to generate energy.

Figure 3.3 shows the shares of the world's oil consumption in million tonnes of oil equivalent (Mtoe) in 1973 and 2015. In 1973, 2252 Mtoe were consumed from which 1.7 % were used by the rail sector, and 5.4 % by the aviation sector. In 2015, the oil consumption of the rail sector was reduced to less than half of its previous value, while aviation amounted to 7.5 %.

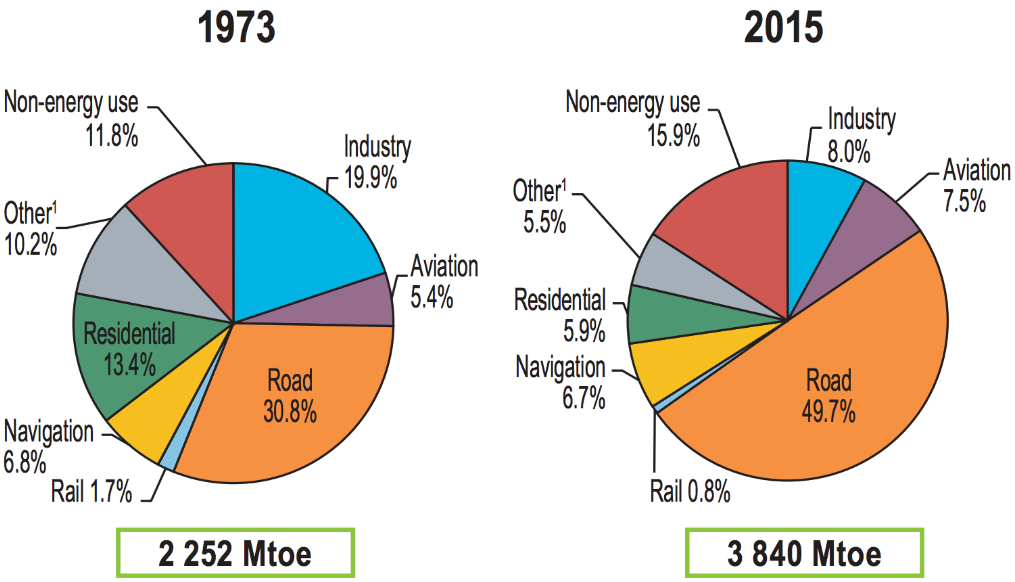

Figure 3.3 Final oil consumption worldwide by sector (in Mtoe) (**IEA 2017**, pp. 39)

For one, the air transport sector has grown drastically, which explains the increase in shares. It also implies the dependency of the air transport sector in fossil fuels to power aircraft engines. However, railway networks have grown and expanded as well, yet the oil consumption decreased. This points toward the potential ground-based transportation systems hold in terms of sustainability.

High-speed train operations are known to be related to two harmful pollutants, sulphur dioxide (SO_2) and nitrogen oxides (NO_x), both of which affect local air pollution, while NO_x is also associated with climate change (**Givoni 2006**, pp. 606). The impact on local air pollution is mainly affected by SO_2 emissions, the level of which generally depends on the share of coal used to generate the electricity to operate high-speed trains (**Givoni 2006**, pp. 606). Power plants are mostly located in areas with a small population density. This implies that the effect of local air pollution through HSR systems is rather small due to the trivial amount of people exposed to it. Figure 3.4 displays the SO_2 emissions in milligram per passenger-mile traveled in a life-cycle analysis. The environmental impact of HSR through sulphur dioxide emissions is nearly four times bigger than that of aircraft, amounting to more than 700 MJ/PMT.

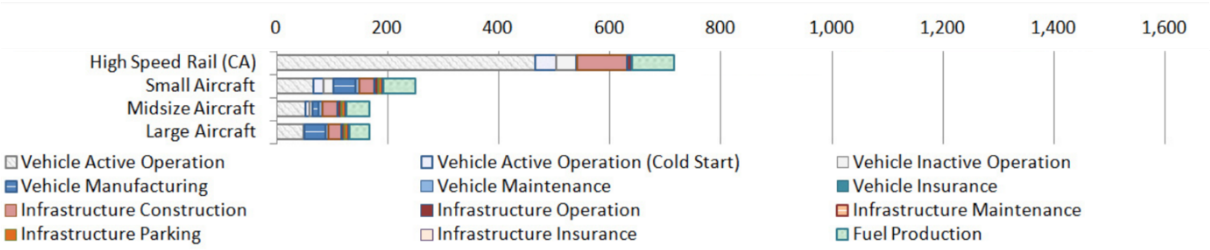

Figure 3.4 SO_2 emissions in mg/PMT (after **Chester 2009**, Figure 3)

The amount of NO_x emitted by high-speed rail systems is rather low compared to the aircraft sector. As shown in Figure 3.5, the most significant amount of emissions is emitted during infrastructure constructions, while aircraft operations alone reach about 600 mg/PMT of nitrogen oxides.

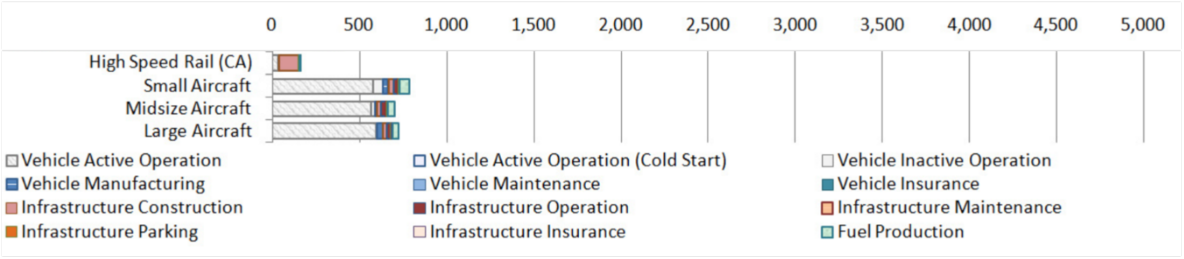

Figure 3.5 NO_x emissions in mg/PMT (after **Chester 2009**, Figure 4)

Because high-speed trains are powered by electricity, the carbon footprint along their operating zones is nearly nonexistent. More importantly is therefore the CO_2 which is emitted during the generation of electricity. This is mainly dependent on the primary energy used to generate electricity which high-speed lines consume. When originated from solid fossil fuels, i.e. coal, the lines have a clearly bigger impact on the environment. The development of renewable energy however can give HSR networks a significant advantage in terms of future sustainability and consequently in the reduction of emissions caused in the process of implementing high-speed rail infrastructure. Figure 3.6 displays greenhouse gas (GHG) emissions in grams of CO_2

equivalent per passenger-mile traveled. Values for CO_2 emissions of HSR *vehicle operations* vary significantly with those of **EC 2010** shown further below.

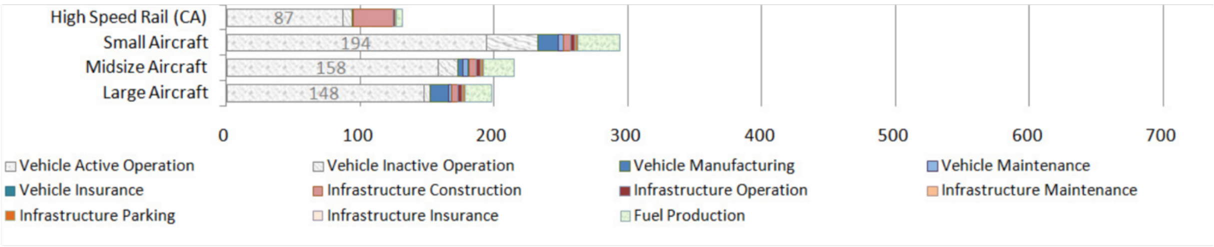

Figure 3.6 GHG emissions in gCO_2e/PMT (after **Chester 2009**, Figure 2)

In 2007, CO_2 emissions attributed to transport systems in the European Union were estimated at about 25.1 %. 0.6 % were emitted by the railway sector, which carried over 6 % of all passengers and about 11% of freight (**EC 2010**, pp. 15). Here again, it is crucial to consider the fact that emissions caused in the process of generating electricity was not taken into account, which actually constitutes the largest amount of emitted pollutants in HSR networks.

A research by the International Union of Railways in 2018 states, that on a 600 km trip airplanes emit 93,0 kg of CO_2 with the consumption of 43,1 liters of primary energy, where high-speed trains only consume 6 liters of primary energy to release 8,1 kg of carbon dioxide (**Leboeuf 2018**, pp. 27). Another study by the **EC 2010** compares the CO_2 emissions in grams per passenger-kilometer (g/pkm) between Marseilles and Paris. The results of the study were also in favor of HST with 2.7 g/pkm, compared to airplanes, which, according to Alstom, cause 153.0 g/pkm (**EC 2010**, pp. 15). These studies primarily prove that along operating lines, the environmental impact due to emission of greenhouse gases, such as carbon-dioxide, are significantly lower in high-speed trains when compared to aircraft.

Table 3.1 Origin of electricity generation by railway 2005 (after **EC 2010**, pp. 15)

Member State	Solid fuels	Oil	Gas	Nuclear	Renewable
Belgium	11.8 %	1.9 %	25.3 %	58.1 %	2.9 %
Germany	54.0 %	0.1 %	8.3 %	26.7 %	10.9 %
Spain	38.0 %	3.8 %	18.3 %	21.5 %	18.4 %
France	4.5 %	1.8 %	3.2 %	85.8 %	4.7 %
Italy	33.8 %	10.0 %	41.5 %	0.0 %	14.7 %
United Kingdom	37.0 %	1.0 %	37.0 %	20.0 %	5.0 %

Table 3.1 lists the sources from which electricity is generated in 6 European countries. With 54 %, compared to the other listed countries, solid fossil fuel were used as primary energy source for the construction of rail networks Germany. This implies that the carbon footprint caused by

the electricity generation for railway systems in Germany comparably high. The energy used on railways in France were mainly generated through nuclear sources with 85.8 %.

Apart from renewable sources, nuclear power plants are known to produce the lowest amount of carbon-based emissions. The disposal of nuclear waste however is argued to have strong negative impacts on the environment. Moreover, accidents at factories have proven to be of great risk to the ecosystem as well. For this reason, the use of nuclear power plants is yet questioned in terms of environmental friendliness and sustainability.

In Spain and Italy, where the use of HSR systems is increasing similarly to other European countries, renewable sources for railway systems make up about 15 % - 18 % of the total energy generation (Table 3.1). Although most countries still rely on fossil fuels, in some cases, a significant amount of energy is already being drawn from environment-friendly resources.

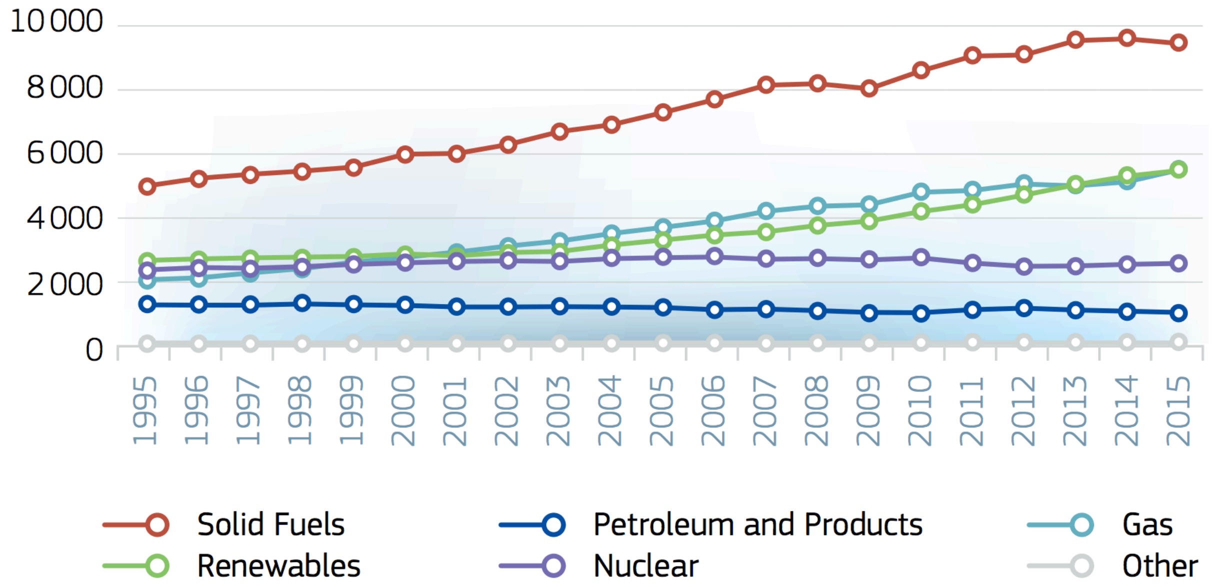

Figure 3.7 World electricity generation by fuel in terawatt-hours (**EC 2017**, pp. 16)

The graph above shows the sources used to generate electricity between 1995 and 2015 around the world. The development over time is measured in terawatt-hours on the vertical axis. Although Figure 3.7 does not refer to sources explicitly used for the generation of electricity in the railway sector, it displays a constant increase of renewable energy sources used on a global scale since 2001. A decrease in solid fossil fuel usage can also be seen since 2013.

This indicates the future potential HSR networks hold, due to the environment-friendly compatibility the systems already present. Conclusively, the use of the electrically powered high-speed trains could reduce emissions in the future, depending mainly on the duration the process of switching to less harmful energy resources will take.

Furthermore, as **Albalate 2010** stated (pp. 24), it is imperative to consider the substitution effect and the traffic generation effect of the transportation modes to further assess the environmental benefits when introducing HSR infrastructure. This means that information about previously used modes of travel by passengers who were shifted to HSR is necessary, and additionally how much newly induced demand was generated.

Environmental concerns associated with aviation are mainly climate change, stratospheric ozone reduction, which leads to higher surface UV radiation, regional and local air pollution and noise disturbance. Aircraft engines emit a variety of chemicals during flight, some of which are carbon dioxide, oxides of nitrogen, sulphur and hydrocarbons. Through these emissions the chemical composition of the atmosphere can undergo alterations (**RCEP 2002**, pp. 10).

The impact on the climate and therefore on the environment from air traffic is not only dependent on the amount and type of emitted species, but is also related to the altitude, latitude and underlying atmospheric conditions of aircraft operations. $N0_x$ emissions for example at high altitude affect climate change much more than emissions at ground level. These various factors make the comparison between the two modes in terms of emissions and their severity difficult to assess.

Noise nuisance from high-speed rail operations are considered to be the main environmental impact along the lines. The nuisance noise causes depends largely on the speed of the HST. Rolling noise makes up the most significant part of the trains between 50 and 300 km/h, which is mainly determined by the smoothness of the wheels and railhead. When operating above 300 km/h, noise due to aerodynamics becomes the primary source causing the environmental impact (**Brons 2003**, pp. 173). Operation speeds are mostly reduced before reaching densely populated areas to stop the HST at the station. This is done far before stopping the train, and therefore decreases the environmental impact at regions where people reside. Furthermore, through the construction of barriers, tranches or tunnels, a significant amount of noise can be blocked and reduced from residents living nearby railroads (**Givoni 2006**, pp. 607).

4 Infrastructure

The infrastructure for air services and high-speed rail operations enables the unique type of mobility of each mode. Aircraft use regulated airways to transport passengers or freight between airports, while HSR systems run over networks of railways over ground, with possible intermediate stops at stations along the lines. The nature of both types of transport is intrinsically different and both types satisfy different requirements, which is, as it why no clear advantage exists of one over the other.

While the fundamental differences between the two types are part of the discussion below, the setup costs for the infrastructure of high-speed rail systems are discussed in a dedicated section further below.

4.1 Air Transport Infrastructure

The infrastructure of the air transport sector enables the transport of passengers and freight over air links, which can be connected over a network of nodes, both domestic and internationally. It generally involves airports and the infrastructure required within to facilitate air travel (**Hussain 2010**, pp. 19). This comprises air traffic control centers and the organizations which coordinate their allocation and use. Airport operators regulate the ground-handling services through space and resource provisions between airlines, their handling agents and commercial concessionaires (**Hussain 2010**, pp.19). Other responsibilities like security, safety and rescue procedures are also assigned to airport operators (**Hussain 2010** , pp. 5).

For commercial flights to take place, facilities for landside and airside have to be realized. For that reason, a large amount of space for an airfield or runways, hangars, terminal buildings, fixed base operator services and air traffic control is necessary. In addition, passenger facilities such as restaurants and lounges are required due to incidentally long waiting times, as well as emergency services in case of urgent situations (**Hussain 2010**, pp. 21). All these facilities necessary at an airport are located at a single, yet large location, which has to be established only once before offering transportation services. Since airports are usually located rural regions, conceivable projects for expansions, when deemed necessary, can be realized with less difficulties.

The regulation of airways allows air services to make efficient use of airspaces at given altitudes, enabling operations at higher security and safety levels. The expansion of airlines and their services is therefore bound to the ground-based air traffic controllers, which manage the airways. This implies, that once an airport is set up, the “roads” over which aircraft operate mainly depend on national allowances for passage and air traffic control systems. As a result, hub-and-spoke structures from which many airlines benefit, can be established with less difficulty than ground-based transportation systems, granting a higher level of national and international connectivity.

Significant advantages of air transport, apart from long-haul travel, is the possibility to operate at high velocities overseas and also to make remote areas accessible. In these cases, air transport cannot be competed with, since ground-based transportation modes are either far slower than aircraft (navigation) or lack the means to overcome geological issues such as mountains, forests, rivers or lakes without high investment costs for the necessary infrastructure.

4.2 High-Speed Rail Infrastructure

Rail-systems set the foundation on which high speed trains can function in such an efficient way as mentioned in the second chapter of this thesis. Therefore, for the implementation of HSR systems, the construction of high-speed lines (HSL) and several high-speed train (HST) stations at certain distances is necessary. Usually, this implies facing problematic circumstances for land acquisitions and mostly dealing with complex situations regarding the construction or upgrade of the rail lines due to environmental obstructions. Rail-systems set the foundation on which high speed trains can function in such an efficient way as mentioned in the second chapter of this thesis.

Countries all over the world face dissimilar challenges when introducing HSR infrastructure. First and foremost, the possibilities to implement high speed lines have to be clarified. Typical geometric characteristics taken under consideration for the construction of these are the maximum gradient, minimum curve radius, track center distance and the maximum cant of the routes. Some tracks are not only meant to be used for passenger transport but additionally for freight. In these cases the geometric characteristics vary, since the power of the trainset allows a steeper gradient for passenger transport only (**Leboeuf 2018**, pp. 44-45). Furthermore, a distinction is made between two types of tracks. Ballasted tracks are less costly and come with a long-term experience of usage, but require permanent maintenance, where slab tracks almost require none, but are noisier and come at a higher price.

High-speed rails and conventional rails can be clearly separated and have each their particular infrastructure in the *exclusive exploitation* model. In the second model, named *mixed high speed*, conventional trains operate only on their according tracks, while high-speed trains can run on either their specially built lines or upgraded conventional ones. In the *mixed conventional* model high-speed trains are only able to operate on HSR lines, while conventional trains run on both track systems. Conventional and high-speed trains can both operate on either infrastructure in the *fully mixed* model (**Campos 2009**, Figure 1). Figure 4.1 illustrates the four models.

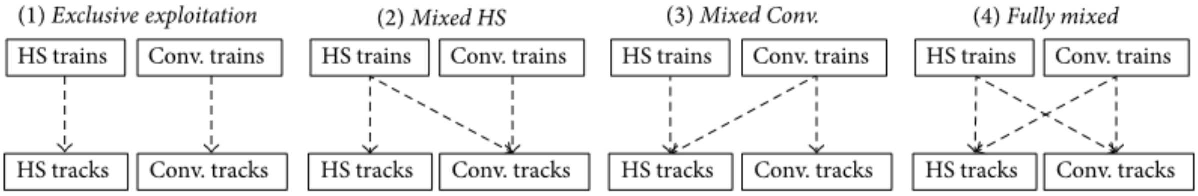

Figure 4.1 Four types of HSR track-models (**Sun 2017**, Figure 2)

The foreseen speed of the lines is also an important indicator, since higher speed limits require a certain infrastructure. For example, signaling and communication systems must be more advanced, and therefore come at a higher price.

Apart from the trains and the rolling stock, various stations and railway maintenance and work sites, the superstructure for HSR networks makes up a large part of the costs which are involved to realize the necessary infrastructure. Table 4.1 shows typical components of the superstructure used for high-speed rail.

Table 4.1 Superstructure components (after **Leboeuf 2018**, pp. 44)

Rail	60kg/m welded
Ties	Concrete monobloc or bi-bloc 1666 per km
Fastening	Elastic
Turnouts	Movable or fixed crossings
Signalling	Above 200 km/h, on-board signalling system
Electrification	Simple phase 25kV, 50 or 60 Hz or 15 kv, 16 2/3

For HSR networks to be efficient on the long run, great emphasis is placed on interoperability and anticipatory designs. Because of diverse system layouts due to differences in national regulations, internal rules and technical specifications i.e. unalike gauge distances or signaling systems, the Directive of the European Parliament expressed the importance of interoperability partly as follows:

> *The pursuit of interoperability within the Union rail system should lead to the definition of an optimal level of technical harmonisation and make it possible to facilitate, improve and develop international rail transport services within the Union and with third countries, and contribute to the progressive creation of the internal market in equipment and services for the construction, renewal, upgrading and operation of the Union rail system (**EU 2016**, L138/44)*

4.3 Comparison of Infrastructures

Given the discussion of the different infrastructures above, the following comparison can be made:

Air transportation has the advantage that it operates on “virtual” rails in the sky that do not need to be built in advance. Thereby, air traffic routes can be easier readjusted or recalculated. At the same time, the “virtual” nature of air transport routes allows to reach remote places more effectively than through a rail-based infrastructure if they are located behind large-scale obstacles (such as mountains, sees or large forest areas).

In contrast, HSR would require rails to be built either around, through (e.g. tunnels) or above (bridges) obstacles, which increases costs, material usage and time spent to develop the infrastructure.

Moreover, if railways cross different political territories, this also brings up the question of different standards for building, connecting and operating the rail systems (interoperability). In contrast, an air transport operation only requires the permission to enter a country’s airspace, but is not impacted by local physical infrastructure regulations.

In fact, since aircraft only need a destination and runways (airport), the infrastructure is immediately extended through the building of an airport in the sense of a hub-and-spoke network. However, the fact that aircraft can only target certain locations, and not make stops in between, represents an advantage for rail systems: rail infrastructures are thus able to allow more or less frequent stops along the route (or spokes) in which freight or passengers can be loaded or unloaded.

Air transport also presents the advantage of globalization since their infrastructure is theoretically accessible from every other airport. Because of that, sections all over the world can benefit from such systems. High-speed rail on the other hand spreads far slower and faces problems of interoperability as mentioned above.

Finally, air transport infrastructure requires a high-level security concept (security checks, passport verification, stationing of police at airports) which naturally increases costs and also slows down operations. HSR in contrast are not required to integrate this level of security in its infrastructure and therefore operate at a lower cost in this respect.

4.4 Costs of High-Speed Rail

Campos 2006 (pp. 22) and **De Rus 2011** (pp. 4) state, that according to the International Union of Railways in 2005, the implementation of a new HSR infrastructure can be defined by three types of costs: *planning and land costs*, *infrastructure building costs* and *superstructure costs*. Up to 10% of total infrastructure costs, containing feasibility studies, technical designs, land acquisitions, legal and administrative fees, licenses and permits are categorized as *planning and land costs*. The costs for terrain preparation and platform building are considered *infrastructure building costs*. These depend mainly on the characteristics of the environment where the railways are meant to be constructed on. Projects for bridges, viaducts and tunnels result in high costs ranging from 15 to 50% of total investment. Installation of signaling systems, tracks, communication and safety equipment, catenary, or other rail-specific elements form the final category and are considered *superstructure costs.* System costs of high-speed rail networks are highly site- and project-specific and fluctuate significantly depending on a newly introduced high-speed line or the upgrade of old railways.

To gain a broader view on this matter, general costs spent on the construction of high speed lines should also be taken into account. The Directorate –General for Mobility and Transport estimated costs for the implementation of high speed lines in Europe at around 269 billion between 1996 and 2020. A major part of these lines was financed by the public sector, especially in France, Germany, Italy and Belgium. Investments on a national level and support of the European Union helped funding projects of HSL constructions (**EC 2010**, pp. 12).

On the average, costs per kilometers in Europe lie between 15-40 million euros but these values vary depending on influencing factors as mentioned above. Table 3.1 shows construction costs of various countries, excluding planning and land costs. **Campos 2009** divides countries in Europe into two groups. France and Spain have slightly lower construction costs than Germany and Italy. These groups differ not only geographically but also in terms of construction procedures. In the case of Italy, high population density, dense urban structures, mountainous terrain and high seismic risk are decisive contributors to the European infrastructure costs of high-speed lines mentioned above (**Albalate 2010**, pp. 20). In General, construction costs in Asia are higher than in Europe with China being the only exception.

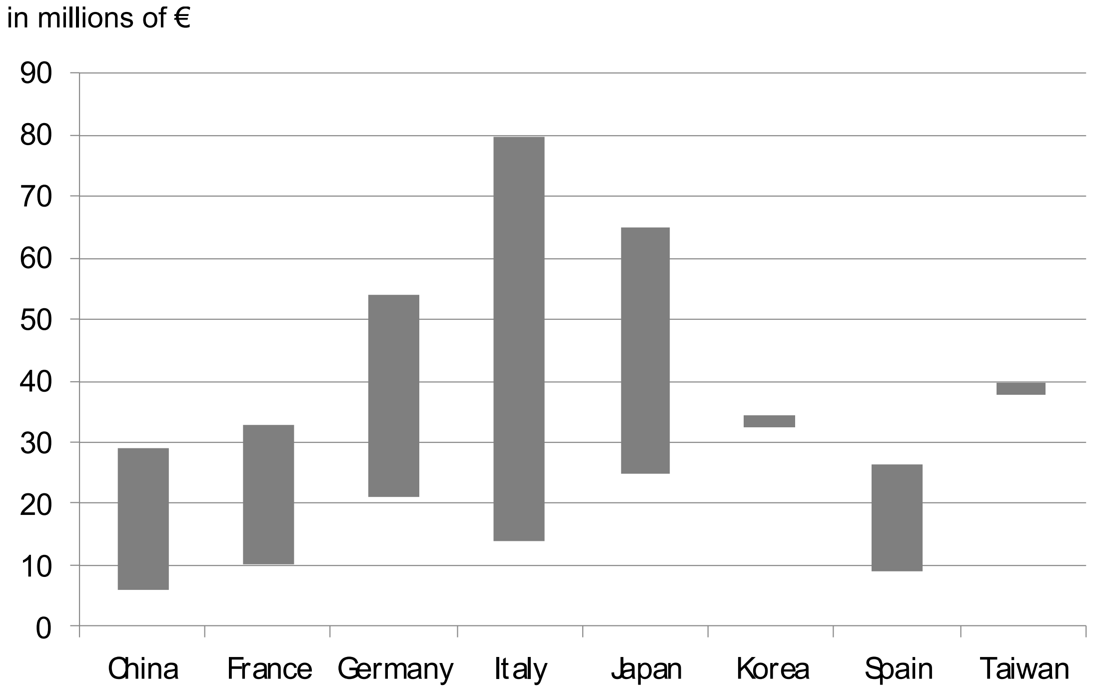

Figure 4.2 HSL construction costs (after **Campos 2009**, pp. 23; **Ollivier 2014**, pp. 7)

Because of the often imprecise and vague data available on the construction costs in the United States and the United Kingdom, costs per kilometer of these countries were not included in the table shown above.

Particularly in the UK and some states of the US, the shape and quality of landscapes are strongly impacting costs. Frequent changes in altitude and the need for numerous tunnels result in high expenses for the construction of high speed lines. Furthermore, many routes cannot be considered feasible due to environmental or historical intrusions. The United Kingdom is therefore a good example demonstrating the possible challenges and reasons why HSR can either be an unenforceable or a very costly project in some cases (**Button 1993**, pp. 542).

The opposite can be observed in Spain, where land and labor costs are particularly low, and additionally, government land is often made available for transport projects (**Gleave 2004**, pp. 37). Also in China, with an estimated 13-20 million euros per kilometer, costs for the construction of HSR lines are significantly lower than in Europe and with the current economic upturn of the country the expansion of HSR infrastructure has reached new heights. For instance, the process to manufacture slab track was brought in from Germany, but due to large volumes and comparably low labor costs, the expanses in China are about a third of what is spent Germany (**Ollivier 2014**, pp. 8). Massive investments are being arranged in high speed rail networks, increasing the reach even to smaller cities with a smaller population and by doing so developing and enhancing their transportation infrastructure. In 2013 China reached 20.318 km of high speed lines in operation and construction, which was five times bigger than the network of Japan and/or Spain (**Feigenbaum 2013**, pp. 3). China is continuously expanding their HSR systems. Engineers are building expertise and a major part of the equipment is produced in the country rather than being imported. By this, China is gathering know-how in HSR technology to further improve their economic state, primarily preparing for future development and competition in the high speed rail sector (**Schwartz 2013**, pp. 159).

Considering issues of high funding and a number of republican politicians opposing projects to implement HSR in the United States, a lack of expertise and investment has resulted in undeveloped high speed rail systems in California and the northeast corridor. Since distances between dense cities in the United States are comparably higher than in Europe for example, the expenses for the implementation of HSR lines are also notably higher. Costs per kilometer in the U.S. for the construction of high-speed railway lines vary tremendously. With an estimation of about 1 million Euro per kilometer for the improvement of existing tracks in the Midwest , 17 million Euro per kilometer to reduce the travel time between Washington DC and New York City by half an hour and 56 million Euro per kilometer for the Los Angeles – San Francisco project (**O'Toole 2009**). Noteworthy is that bringing the lines through mountains would require higher investments, pushing the average expenses per kilometer up significantly in the case of the Los Angeles and San Francisco project (**Peterman 2013**, pp. 18).

As it can be seen, investing in HSR can be a costly process and, depending on various factors, costs for the implementation can differ greatly. Furthermore, even on national scales, costs when building high-speed lines vary greatly. Expenses for the Tokyo – Osaka Shinkansen i.e. were around €5.4 million per kilometer in 1964. Compared to the following years these costs nearly quadrupled. In France each kilometer for the TGV Sud-Est between Lyon and Paris cost around €4.7 million in 1981. In 2001, with the inauguration of the TGV Méditerranée, costs amounted to €12.9 million per kilometer. Therefore, because of differences in characteristics of each HSR project, comparisons, especially on a global scale, should be made with caution (**Campos 2009**, pp. 23).

In summary, infrastructure investments must provide an improved mobility and accessibility across the network with a minimum environmental impact. For HSR projects to be justified and acknowledged as useful or necessary developments by the public, the various aspects mentioned in this thesis mentioned in the course of the comparison need to be considered. The following chapter will provide a deeper look for the reader into these decisive determinants and discuss how value assignments come about.

5 Modal Choice of Travelers

5.1 Selection Criteria

With the use of conducted surveys in France, Spain and the United Kingdom, key parameters that determine the modal choice of travelers in Europe have been formulated. 2000 respondents of a focus group in each country were used to devise the chart. To ensure that the data set is representative of the nation, statistical adjustments have been realized. For this, age, gender, social grade, region of residence and the possession of a car have been considered. The respondents of the survey could select 5 of the 14 given criteria. The graph makes it clear, that the price and the travel time are the main determinants for the modal choice. Table 4.0 shows the parameters assorted by importance of the surveyed.

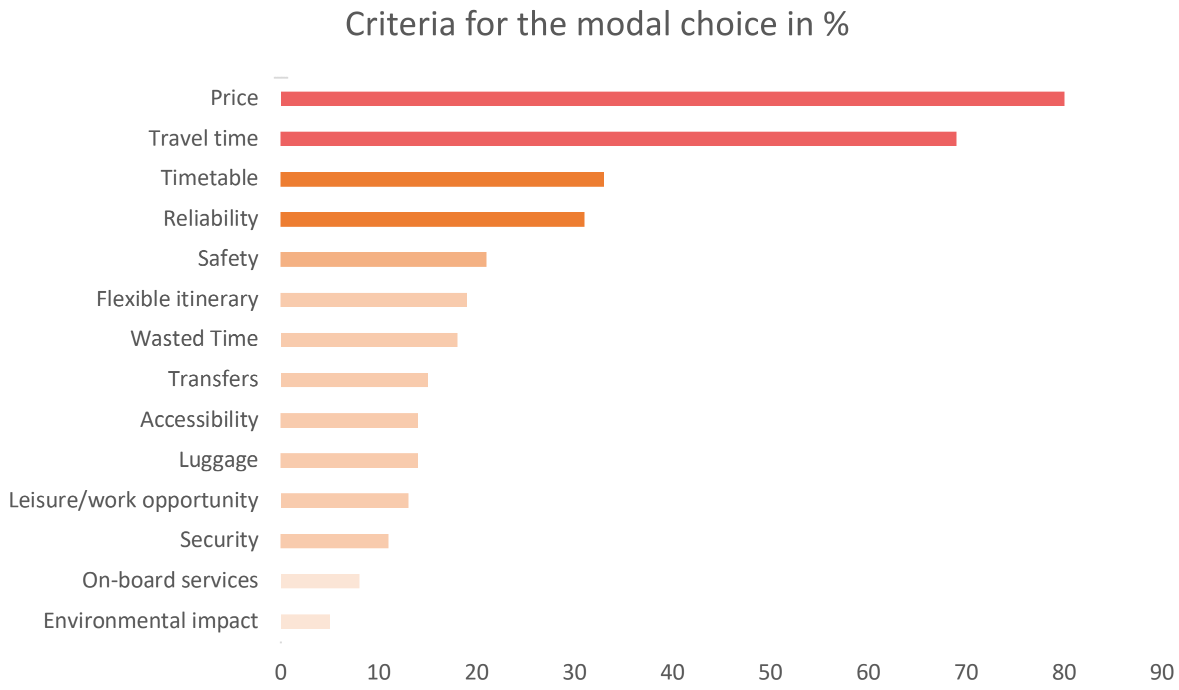

Figure 5.1 Selection Criteria for mode of travel (after **Leboeuf 2018**, pp. 20)

As it can be seen in Figure 5.1, the main criteria that determines the modal choice of passengers are the travel expenses, the travel time and the service frequency, followed by the reliability and the safety of the service. The service frequency is labeled as “Timetable” in the graph shown above. A rather small impact on the modal choice for passengers is the accessibility and the environmental aspect of the transportation type. These two elements still prove to be very important, because of their economic significance. The improvement in accessibility results in a higher level of interconnectivity, making all sorts of necessary infrastructure and jobs easier accessible for people residing in rural areas for example. Furthermore, the environmental impact is rather a more interesting aspect for politicians favoring a cut in emission exhaust then travelers.

In the following subsections, the main criteria for the modal choice will be investigated to draw comparisons between the air transport sector and high speed rail systems. Therefore, busy routes with comparably high service frequencies traveled by aircraft and HSR in selected countries will be compared, primarily using the first four selection criteria worked out by the survey of the UIC.

5.2 Itinerary Research

Based on the work of **Sun 2017**, where a direct comparison between the Beijing and Shanghai route has been made, using the same time and destination of departure to travel to a specific location with both air transport and HSR, further investigations has been conducted. For this, a central location in Beijing, the Capital Times Square was selected by **Sun 2017** as the place of departure. As destination, the Shanghai airport Hongqiao, being situated at a rather rural area, about 18 km outside of the city center, was used. In this case, high-speed rail reaches its destination about 30 minutes earlier than with air services, although the ground distance is more than 1,200 km. This research shows how the competition range between HSR and air transport has increased substantially in China (**Sun 2017**, Figure.1).

To draw further conclusions about markets in other regions, additionally to the Beijing – Shanghai itinerary, five other routes have been compared using the same systematic as **Sun 2017**. Since most of the routes traveled, are from one central location to another, the routes used for the comparison were selected as such. Based on Table 5.1, showing the passenger-km traveled in billions by high-speed rail between 2010 and 2017, the five countries with the highest amounts of which have been selected. Furthermore, an exemplary country which has proven difficulties establishing high-speed rail services was chosen to evaluate the efficiency of its underdeveloped network.

Table 5.1 High-speed traffic in the world in passenger-km in billions (after **UIC 2019**)

Year	2010	2011	2012	2013	2014	2015	2016	2017
China (China Railway)	46.3	105.8	144.6	214.1	282.5	386.3	464.1	577.6
Japan (JR Group)	76.9	79.6	84.2	87.4	89.2	97.4	98.6	101.4
Korea (Korail)	11.0	13.6	14.1	14.5	14.4	15.1	16.3	14.9
Taiwan (Taiwan HSR Corp.)	7.5	8.1	8.6	8.6	8.6	9.7	10.5	11.1
France (SNCF)	51.9	52.0	51.1	50.8	50.7	50.0	50.5	58.3
Germany (DB AG)	23.9	23.3	24.8	25.2	24.3	25.3	27.2	28.5
Spain (Renfe Operadora)	11.7	11.2	11.2	12.7	12.8	14.1	15.1	15.5
Italy (Trenitalia + NTV)	8.0	8.3	9.6	11.6	11.7	13.6	14.3	15.1
Other European Companies	7.3	10.5	14.8	15.2	18.2	20.0	22.0	22.4
Total	244.6	312.6	363.0	440.1	512.4	631.4	718.7	844.8

On a specific working day, the 17th of April 2019, itineraries in China, Japan, France, Germany, Spain and USA were researched. To obtain useful results of the comparisons, the routes chosen in each country were based on several factors. For one, itineraries with a similar ground distance between cities were looked into, with the exception of China. In the case of the Beijing – Shanghai route, other factors overweighed the distance, such as operating speed and general passenger demand. In order to evaluate the competitiveness with air travel, the success and the popularity of the high-speed lines play a major role when choosing routes to compare. This was mainly estimated through shifts in modal shares or an increase of passengers-km traveled by HST based on the research of **Givoni 2006**, **EC 2010** and **Bullock 2012**.

To include the service frequency as a deciding factor when comparing travel modes, the time of departure from each location was set on 8:20 am. Figure 5.2 shows the researched itinerary between Berlin and Munich. The first travel route labeled with (a) underneath displays the schedule using air travel, following with the option with high-speed rail.

Time	Location	Mode	Price
08:20			
08:21	Berlin Central Station		
	|	RB21 Regional Line	…
08:25	S+U Zoologischer Garten		
08:33	|		
	:	Bus X9	2.80 €
08:52	Berlin Airport Tegel		
09:00			
10:00	Berlin Airport Tegel		
	|		
	|		
…	:	Lufthansa LH2033 (every 9.25 min)	110 €
	|		
11:05	Munich International Airport		
11:43	|		
	:	S-Line Metro	11.60 €
12:45	Munich Central Station		
04:25 h			124.40 €

(a) Travel mode: metro + bus + aircraft

Time	Location	Mode	Price
08:20			
08.30	Berlin Central Station		
	|		
	|		
…	:	ICE 505 (every 47 min)	67,90 €
	|		
13:02	Munich Central Station		
04:42 h			67,90 €

(b) Travel mode: high speed rail

Figure 5.2 Berlin to Munich itinerary

Building on the layout of **Sun 2017**, a detailed research between two central locations has been conducted. Costs between destinations for each step of the routes have been investigated. Sections under the price column showing three dots imply that costs for the route are included in the following trip's expenses and therefore can be paid as a combined journey with one or more intermediate stops. Additionally, the main focus of the research and comparison between HSR and air travel itineraries was set on finding the shortest possible travel duration. Although costs for the fares are of greater significance in Europe, this does not apply on a global scale. Furthermore, placing the emphasis on the pricing would result in massive distortions of the travel duration, since ticket prices in the aviation sector can be far cheaper when considering long waiting times for the journey. However, the same does not apply when focusing on the minimum travel duration; ticket prices remain closer to the average amount of usual fares. Ticket prices have only been researched in the economy classes of offered services for both modes of transport.

For reasons of greater clarity, the results of the itineraries have been brought together in Table 5.2. The remaining researched routes are included as an appendix to the notes.

Table 5.2 List of researched itineraries (source: researched itineraries from appendix)

Travel Mode	AT	HSR	AT	HSR	AT	HSR	AT	HSR	AT	HSR	AT	HSR
Country	China		Japan		France		Germany		Spain		USA	
From - To	Beijing - Shanghai		Tokyo - Osaka		Lyon - Paris		Berlin - Munich		Barcelona - Madrid		New York City - Washington DC	
Approximate Distance in km	1.000	1.200	400	500	400	425	480	505	504	617	328	365
Travel Duration in hours	06:27	05:47	03:53	02:45	08:45	02:41	04:25	04:42	04:53	03:25	05:51	03:39
Price in Euro	186.20	84.30	79.30	115	307.20	75	124.40	67.90	74.90	87.30	100.69	153
Frequency in minutes	28.2	14.5	30	6	19	40	9.3	47	11	44	88	76.5

In the following subchapters, the four main criteria for the selection of a transportation mode by passengers are shown in Figure 5.1 and the obtained results listed in Table 5.2 will be compared and discussed.

5.3 Travel Expenses

In Europe, travel expenses are the first and most important aspect considered when traveling. Affordable tickets are therefore a necessity to ensure the usage of a transportation mode. Ticket prices of high-speed rail networks are mainly determined by construction and maintenance costs. In general, low construction costs therefore result in more profitable HSR projects, since affordable ticket prices can be offered, usually enabling a larger amount of passengers the use of the system. A good example represents China, where labor costs and construction costs for tunnels are significantly lower than in other countries, resulting in low ticket fares, as it can be seen in Table 5.2 and 5.3 further below. Furthermore, ticket prices between Beijing and Shanghai do not vary over time, the fare of 74 € remains the same. In countries like the United Kingdom or the United States the same applies. High construction costs resulted in high ticket fares and unprofitable HSR projects. Yet in some countries, although the construction costs are relatively high, high-speed rail has proven to be a profitable investment. In the case of Japan, while

HSR is still a more expansive means of travel compared to journeying by aircraft, the service frequency is much higher. This indicates that the price is not the main determinant of the modal choice in Japan, other factors are more important to passengers.

Between Lyon and Paris air travel is quite costly. Fares for high-speed rail are significantly lower. Table 5.3 shows the average costs for fares of both HSR and air travel. Clearly, the average price using high-speed rail for the Lyon – Paris route is far cheaper than the average airline ticket. Noteworthy is also, that in this case only four direct flights are offered between Lyon-Saint Exupéry Airport and Charles de Gaulle Airport in Paris.

For the itinerary from Berlin to Munich, ticket prices vary between approximately 64 € and 98 € using high-speed rail services, mainly depending on the time of departure. An average of 84 € with direct access to the city center in Munich makes the Intercity-Express an attractive mode of travel between these cities, even though the travel duration exceeds that of the available air service shown in Table 5.2. The difference in average ticket fares between air travel and HSR amounts to 22 €.

Deducing from Table 5.2 and 5.3, similar to the itineraries in Japan and the USA, average ticket prices in Spain for high-speed rail services are higher than in the aviation sector, but in exchange the total travel time is less using HSR. Even though the popularity of high-speed rail in the United States is not comparable with the majority of countries which offer HSR services, the comparison between the two modes of transport in terms of average ticket prices indicates that there is an existing potential of growth in demand. Differences in average prices of national flights and the Acela Express are about 17 €, with the high-speed train having the advantage of direct accessibility to city centers with less total travel time.

Table 5.3 Average ticket fares (“count” stands for the amount of itineraries from which the average was calculated)

Itinerary	Beijing - Shanghai	Tokayo - Osaka	Lyon - Paris	Berlin - Munich	Barcelona - Madrid	New York City - Washington DC
Average ticket fare HSR (in €)	74	115	48	84	74	134
count	34	25	22	23	23	16
Average ticket fare AT (in €)	190	106	213	106	67	117
count	38	36	54	22	21	10

In many cases, with the introduction of HSR, airlines reduce their ticket fares to secure market shares. Due to various other influencing factors, this might not result in the securing of market shares for airlines (**Albalate 2014**, pp. 4-5). Reviewing the results from comparisons of each itinerary, major international differences are apparent. Nevertheless, it becomes obvious that ticket fares play a significant role when deciding the mode of transport, but even as the main determinant in Europe, cheaper fares of HSR or air travel services do not result in one mode of transport definitely gaining significant market dominance. Further assessments considering the remaining influencing parameters are necessary.

5.4 Travel Duration

As second most significant determining factor for the modal choice of passengers, the travel time was chosen by 69% of the surveyed in Europe. Although the travel time spent on an aircraft is still far less than that of high-speed trains, in many cases the advantage of accessibility influences the total travel time when traveling with HSR. Since most final destinations of passengers are located in rather dense city centers rather than rural areas, journeying with high-speed rail allows travelers to directly access those without changing the mode of transport. The opposite applies when using air travel on the itinerary. The infrastructure of airports requires a large and flat space and is therefore mostly located in rural areas, distant from city centers. This means that passengers are required to change the mode of travel at some point. Moreover, HSR allows passengers to access various locations in rural areas by the provision of numerous stations along routes.

In Japan, among other factors, travel time is one of the most substantial criteria for the modal choice. Following the historical development of the Tokyo – Osaka route, the significance of reducing the travel duration becomes more apparent. Before high-speed trains were introduced in Japan, it took around 7 hours to travel between Tokyo and Osaka. After the Shinkansen started operations, the travel time decreased to 4 hours, and since 1992 the total travel duration for the itinerary is approximately 2 hours and 30 minutes (**Givoni 2006**, pp. 600). Comparing the reduction of the travel duration with the increase of service frequencies, the importance of the travel time becomes more apparent. Moreover, air services between Haneda and Nagoya were abandoned after the inauguration of the Shinkansen between Tokyo and Osaka (**Taniguchi 1992**, Table 4.).

Using air services, and especially when traveling with luggage that has to be checked-in, a large amount of time is lost due to boarding and check-in processes. In addition, security checks can be very time-consuming at certain hours, particularly at times of high service frequencies. For the researched itineraries shown in Table 5.2, using air services on the route, rather short time frames were chosen to change the mode of travel. This was done to offset the advantage given to HSR where the destination of the compared itineraries was directly accessible through a high-speed line.

Apart from the Berlin – Munich route, the total travel time between the selected cities shown in table 5.2 is less when traveling with high-speed rail. When traveling on a plane from Berlin to Munich, the travel time is 17 minutes less than by HSR, but includes changing the mode of transport 3 times. Considering the survey conducted by **Leboeuf 2018** (pp. 20), 18% selected *wasted time* as a criteria for the modal choice, which in this case would apply due to the numerous times the transportation type would have to be changed by the passengers.

In the case of the Acela Express, interesting results were obtained comparing the two modes of transport. Despite the fact that the high-speed train in the Northeast Corridor running between Boston and Washington DC only operates on a small segment at the top speed of 247 km/h, it reaches its destination 1.12 hours earlier than traveling on an aircraft. This proves that even in countries where HSR is having issues of implementation on a national scale, the services provided have the potential of further growth.

Based on the research listed in Table 5.2, using air travel as a mode of transport between Lyon and Paris results in extremely high travel time. Even though the service frequency of the TGV averages at 40 minutes, being more than half of the amount of offered air services, the travel duration reaches 8 hours 45 minutes, which takes about 6 hours longer than traveling with HSR. Between the two researched airports only very few direct flights are offered, which leads to long waiting times in between flight connections.

5.5 Service Frequency and Reliability

Over 30% of the surveyed by **Leboeuf 2018** selected the service frequency and reliability of the transportation mode as a determining factor for the modal choice. Three of the researched itineraries listed in Table 5.2 show higher service frequencies when using HSR. Between Beijing and Shanghai, the amount of service frequencies of high-speed trains is twice as much as that of aircraft. In Japan the Shinkansen between Tokyo and Osaka operates every 6 minutes, 5 times the amount of air services available between Haneda and Osaka Itami airport. The route between New York City and Washington DC shows higher service frequencies using the Acela Express, when compared with the itinerary traveling between John F. Kennedy International Airport to Ronald Reagan Washington National Airport.

In the 3 European countries air service frequencies are still higher than in HSR networks. In the case of Lyon – Paris the data is not applicable due to indirect flights being included to the count. On average, only 4 direct flights operate between the cities. Between Berlin and Munich the aircraft are still running in high frequencies, more than 4 times the amount of high-speed trains connect the two cities on a working day. The same applies to the Spanish route. The air service frequency is 4 times higher than high-speed operations run by Renfe Operadora.

Table 5.4 Urban area population and population density

City (Urban Areas)	Land Area (Square Kilometers)	Population Density (Per Square Kilometer)	Population
Tokyo-Yokohama	8547	4500	38,050,000
Osaka-Kobe-Kyoto	3238	5300	17,165,000
Beijing	4144	5100	21,250,000
Shanghai	4015	6000	24,115,000
Barcelona	1075	4500	4,840,000
Madrid	1360	4700	6,385,000
Berlin	1347	3100	4,120,000
Munich	466	4400	2,045,000
Lyon	1178	1400	1,665,000
Paris	2845	3700	10,980,000
New York NY-NJ-CT	11875	1700	21,575,000
Washington DC-VA-MD	3424	1300	5,180,000

Table 5.4 shown above lists all cities as part of an urban area which were used for the comparison of itineraries. For each urban area the population, population density and the land area is listed in a row. It is noteworthy, that mainly accurate data on urban areas and city compositions is available. The listed values therefore relate to much larger covered areas. Yet it is apparent that high service frequencies are in direct relation to the population density of the shown urban areas. In the case of Tokyo to Osaka, where HSR operates approximately every 6 minutes, the population density is very high. It is important to compare the population density to the land area. In Tokyo 4500 people live per square kilometer (km^2) on a total land area of 8547 km^2. This indicates a higher population density in city centers. Comparing the values of Tokyo with Barcelona, where also 4500 people live per km^2, the land area is much smaller with 1075 km^2, implying a much greater population density in Tokyo. Concluding from Table 4.5, service frequencies are a more decisive factor for the modal choice in cities with higher population densities such as Beijing, Shanghai and Tokyo and Osaka.

Up-to-date signaling systems allow HSR systems to operate with relatively short headway between trains without causing safety issues. This allows dense cities like Tokyo to provide services at top speed limits at such short frequencies (**Givoni 2006**, pp. 600).

Another significant influencing factor when choosing a mode of travel is the service reliability. 31% of the surveyed by **Leboeuf 2018** selected the reliability as a criteria for the modal choice. Air services face numerous issues causing disruptions in operations. Many of these are stochastic in nature and unpredictable. For one, airlines have to deal with late connecting passengers, baggage due to late inbound aircraft, missing check-in passengers or late arrivals of previous aircraft. On the other hand, delays can originate at airports due to capacity constraints, air traffic control or technical maintenance issues. Major disruptions are also caused by large-scale airport closures because of storms or security concerns. Managing an airline schedule is a complex task. Airlines try maintaining high schedule on-time performance (OTP) due to its critical influence on the travel experience of passengers, especially delay-sensitive travelers tend to question the reliability of an airline when dealing with off-schedule flights. Furthermore, delays can result in high costs for airlines. For these reasons the continuous optimization of OTP is of great importance (**Wu 2005**, pp. 274).

Delays in HSR systems are generally caused by signaling failures, issues due to rolling stock or tracks. Similar to air services, accidents are rather uncommon and mainly caused through environmental problems such as storms or earthquakes. The punctuality of the Shinkansen has proven that high-speed trains can run with very low delay averages. The same applies for the Taiwan High-Speed Rail (THSR) and the Korean Train eXpress (KTX). As shown in Table 5.5, even with the high probability of natural catastrophes included in the value, an average of 0.6 minute delay per train is reached by the Japan Railways Group (**Jong 2010**, pp. 179). The THSR imported 700T trains from Japan, a type of the Shinkansen rolling stock from the 700 series. With the use of the foreign technology the average delay and punctuality of the Taiwan High-Speed Rail exceeded that of Japans.

Table 5.5 Punctuality and average delay (after **Jong 2010**, Table 2)

/	Punctuality (within 5 min)	Average delay per train
Shinkansen	98,30%	0.6 min/train
KTX	94,10%	/
THSR	99,25%	0.216 min/train

In the case of aviation, the on-time performance represents the punctuality of flights. If the aircraft operates in less than 15 minutes shown in the scheduled time of the carriers' Computerized Reservations Systems, the performance is considered "on-time". In comparison with high-speed rail, in 2017 on-time performances in terms of the arrival time for airlines fluctuated between 90% - 80% for mainlines and 85% - 73% for Low-Cost Carriers. Moreover, when compared with the world's largest airlines, the Japanese carriers Japan Airlines and All Nippon Airways reached the highest OTP with 85.27% and 83.81% in 2017 (**OAG 2018**). This again points out the regional difference, showing that the reliability of provided services in Japan is of higher importance.

5.6 Accessibility

Usually, high-speed rail networks, similar to many airlines, are developed in a of hub-and-spoke pattern, where rural areas get linked to hubs, which are mostly large and dense cities. Often capital cities are used as a hub, where apart from the size and density, the central location proves advantageous for the tree-like architecture of the network to ensure efficient operations. In the course of time with continuous expansion other cities can be used as secondary or tertiary connecting centers. From the primary hub the maximum number of spokes emanate. Hub-and-spoke networks benefit from the efficient use of scarce transportation resources which allows a more rapid growth of the system.

Levinson 2012 describes two effects of accessibility on the economy. For one, it increases total wealth, since larger aggregate output is achieved through agglomeration economies due to new infrastructure. Secondly, wealth is redistributed because more of the aggregate wealth is gained at locations where the accessibility gains are larger. For that reason, economic opportunities can be lost in cases of deficient accessibility.

On the other hand, it is argued that the implementation of high-speed lines may divert economic activities to large hubs, draining smaller cities with already unfavorable economic conditions (**Givoni 2006**, pp. 605). When improving accessibility for some regions, a downgrading of conventional train and air services on those lines has been discovered. Additionally, while two cities profit from better accessibility, regions between high-speed stations are disregarded, which has been referred to as the *tunnel effect* (**Albalate 2010**, pp. 8). Therefore, it is yet unclear which sectors benefit most from HSR and if economic activity is dispersed throughout the country or rather centered.

However, compared to air services, the possibility of introducing various stations between nodes gives HSR a definite advantage in terms of accessibility for people residing in both rural and dense urban areas. Since high-speed rail enables passengers to travel with a comparably low amount of time being wasted due to waiting, security checks or modal changes, travelers more sensitive to lost useful travel time benefit from the opportunity to travel with less time being wasted.

Airlines have the advantage of making remote locations or islands accessible. The Channel Tunnel connecting the European mainland with the United Kingdom is the only HSR connection overseas, and only has been realizable due to the short distance between the two countries.

6 Maglev Transportation

After having completed the comparison of HSR and air transport, this chapter shall briefly present and discuss the *Maglev* technology, which may be considered to be a “hybrid” form of air and ground transport as it levitates the vehicle while also keeping it in controlled guideways similar to classical railway systems.

In order to stay within the scope of this thesis, Maglev will not be fully contrasted with aspects such as infrastructure, environmental impact etc. but only briefly described and sporadically compared to these aspects to give the reader a broad understanding.

6.1 Magnetic Levitation Technology

Maglev (magnetic levitation) vehicles function without mechanical contact or friction like high-speed trains. They are magnetically levitated and propelled along a guideway, allowing operations at high velocities, limited primarily by atmospheric drag (**Ehsani 2013**, pp. 753). Since Maglev vehicles run without engines, they hold a high potential as an environment-friendly mode of transportation. Without engines, no oil or solid fuel is burnt and therefore no pollutants and greenhouse gases are emitted into the atmosphere when operating. Additionally, the magnetic levitation technology based on repulsion and attraction allows the vehicles to run without contact or engine noise (**Ehsani 2013**, pp. 753).

Through the interaction between AC currents in the guideway and magnets on the vehicle, the train is propelled along the lines. Speed and position of the Maglev is dependent on the frequency of the current. The vehicles are not controlled by on-board engineers, but a central traffic control center, which observes the guideway in real time, controlling the speed and location of all vehicles. This is done by regulating the frequency of the AC propulsion current given to the energized block of the guideway on which each Maglev vehicle operates on (**Ehsani 2013**, pp. 753).

The technology is differentiated between two types: electromagnetic and electrodynamic suspension (**Liu 2015**, pp. 2). For the electromagnetic suspension system the Maglev vehicle uses conventional electromagnets which energize an iron structure to create a magnetic field (**Ehsani 2013**, pp. 753). These electromagnets are positioned underneath two iron rails attached to a T-shaped guideway. The vehicle is levitated through the attractive magnetic force between its electromagnets and the guideway’s iron rails located above them as shown in Figure 6.1.

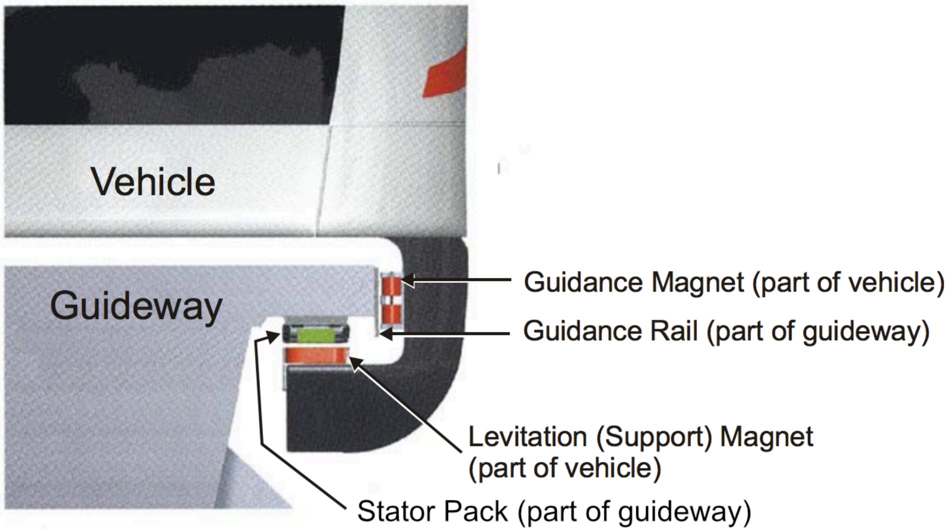

Figure 6.1 Electromagnetic levitation (after **Brecher 2002**, Figure 1-4.)

The technology based on electromagnetic levitation presents some issues. For one, the magnetic suspension is inherently unstable. Minor changes in distance between the magnets and the guideway result in major variations of the attraction force. The current used inside of the vehicle's electromagnets must be adjusted frequently by an additional control system to maintain a safe gap between the guideway and the vehicle. Another concern is the distance of the gap. For the magnet to levitate the vehicle, the distance between the vehicle and guideway must be very small, about 1 cm. Maintaining a steady gap requires high costs for the guideway. Furthermore, electromagnetic levitation has low lifting capabilities because of heavy magnet and power systems, which are necessary for the operations (**Liu 2015**, pp. 2).

The electrodynamic suspension, unlike the electromagnetic system, usually utilizes a repulsive force through permanent magnets on the vehicle. The magnetic field is produced either by conventional permanent magnets or superconducting magnets. The conventional permanent magnets are significantly weaker in strength. As a result, Maglev trains using those have very small gaps between guideway and vehicle, and therefore present limited capabilities to carry heavy weights. With the use of superconducting magnets, the distance between guideway and vehicles is nearly ten times larger than with permanent magnets, providing the vehicle with better weight-lifting capabilities (**Ehsani 2013**, pp. 754).

Superconductive materials are placed on the side of the vehicle which interact with figure-8-shaped coils on the side of the guideway. As the coils experience the change of the magnetic field when the train moves along the line with the superconducting material two currents are induced opposing the change in magnetic field. One opposes the magnet's pole from below, with a repulsive force, the other one from above, through attraction. With the constant magnetic interaction, the train is lifted about 10 cm above ground when operating. Figure 6.2 displays the guidance and levitation system of Maglevs using superconductive suspension (**Mamoru 2016**, pp. 21).

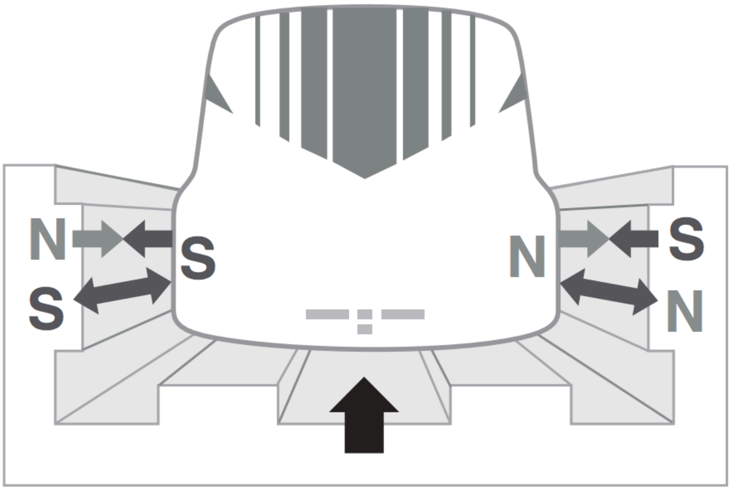

Figure 6.2 Superconductive levitation (**Mamoru 2016**, Figure 9.)

To propel the vehicle, a magnetic field with north and south poles is generated by passing current through the propulsion coils on the ground. As a result, the vehicles is propelled forward by the attraction of opposite poles and the repulsion of same poles which are arranged alternately between the coils in the ground and the superconducting magnets inside of the vehicle as shown in Figure 6.3 (**Mamoru 2016**, pp. 20-21).

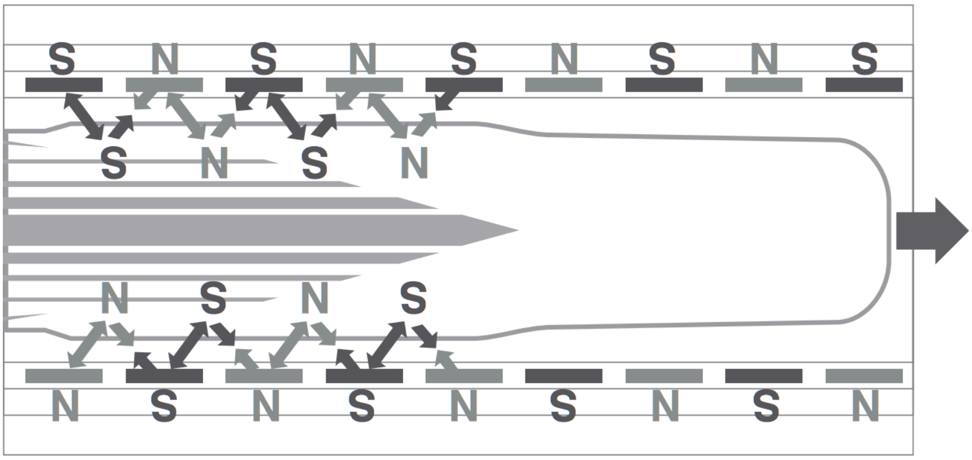

Figure 6.3 Maglev propulsion system (**Mamoru 2016**, Figure 8.)

At certain temperatures, the electrical resistance of some materials reaches nearly zero. When an electrical current is applied to a superconducting coil, a comparably large magnetic field is generated, since the current inside the coil continues flowing almost indefinitely. For this, cooling systems are necessary to ensure low temperatures (**Mamoru 2016**, pp. 20). Additionally, due to the magnets inherent strength, the Maglev can be designed to resist hurricane winds and earthquakes without any contact with the guideway (**Ehsani 2013**, pp. 775).

6.2 Current State

As a precaution against catastrophes such as the Great East Japan Earthquake in 2011, safe lines for high-speed ground transport, impervious to natural disasters, have become important in the case of Japan. For that reason the JR Central has set its focus on completing the Chuo Shinkansen, a Maglev line connecting Tokyo and Nagoya, as fast as possible. The Chuo Shinkansen will initially function as an integrated system with the Tōkaidō Shinkansen, which is currently operating between Tokyo and Osaka (**Mamoru 2016**, pp.14).

In 2003, test trains achieved a record speed of 581 km/h (**Takagi 2005**, pp. 7). This world record was broken in April 2015, when a manned superconducting Maglev train reached 603 km/h in Japan. The travel duration between Tokyo and Osaka is about 2.5 hours using high-speed rail. The test line, *Chuo Shinkansen* will eventually be part of, connecting the two Japanese cities Tokyo and Osaka, is said to reduce the travel time of approximately 1.5 hours. Tokyo and Nagoya are planned to be linked through the Maglev in 2027, at a maximum operating speed of 505 km/h, reducing the travel time to about 40 minutes. The total connection with the extension to Osaka is expected to be ready for operation by 2045. The majority of the 286 km-long route will be located underground (**JRP 2019**).

The Transrapid developed in Germany uses an electromagnetic suspension system. Its technical readiness was approved in 1991 and since December 2003 a Maglev line connecting the Shanghai Airport and the Longyang Road station in Pudong was opened, operating at a maximum speed of 430 km/h (**Lanzara 2014**, pp. 71). Currently two lines using Maglev technology in China, one in Japan and another in South Korea are operating, while in several other countries such as the United States, Germany, Israel and Switzerland the construction of such lines are in process (**Ehsani 2013**, pp. 754).

Apart from environmental benefits the technology entails when operating along the lines, the reduction of travel time is the most significant factor when considering the implementation of Maglev systems, due to high application speeds the trains can achieve. Maglev vehicles also present a higher acceleration capturing as well as climbing ability and a lower environmental impact through noise than conventional railway systems. Furthermore, a smaller turning radius is realizable, which makes the implementation of such trains more applicable in dense urban structures (**Liu 2015**, pp. 13). JR Central has been offering *Experience Rides* on the Yamanashi Maglev line since November 2014. More than 30,000 passengers have taken these test rides at a maximum operating speed of 500 km/h. Participants have given positive feedback regarding the level of comfort (**Mamoru 2016**, pp. 24).

Due to the special infrastructure the Maglev trains require, compatibility with existing railway networks is not possible, what consequently results in high construction costs. Similar to HSR networks, the environmental impact caused by the construction for the Maglev guideways has yet to be researched and taken into consideration to evaluate environmental benefits of such systems. Further research and progress in superconductive materials might improve the current state of the technology, enabling operations at higher temperatures and therefore less refrigeration power, and energy consumption for systems. Such improvements will widen the range of application and simplify the implementation of Maglev networks in the future (**Ehsani 2013**, pp. 802).

7 Conclusion and Recommendations

7.1 Summary and Results

This thesis presented high speed rail (HSR) as a ground-based high-speed transportation alternative to the well-known means of air transportation. Since HSR is a less common means of transport, the focus was laid to a larger extend on the attributes and specialties of HSR before eventually drawing comparisons to air transportation.

Prior to the comparison itself, a literature review has been conducted in which prominent authors and resources were identified. The review revealed that most authors agree that modal shifts from air transportation toward HSR take place. This point has been further discussed and confirmed in the comparison of the two forms of transportation in this thesis.

The comparison between HSR and air transportation was mainly conducted on the basis of four different criteria: (1) Differences in *physical properties and behavior*, (2) *environmental impacts*, (3) infrastructural aspects and (4) *passengers' modal choices*.

In terms of *physical* differences, it was reasoned that rail vehicles have a higher potential in terms of performance efficiency due to the use of steel-based wheel-tracks, which result in a rolling friction that is comparably low when considering the amount of induced drag of an aircraft. Aerodynamic drag may be further reduced for trains via adjusted underbelly fairings. This may be more cost efficient than producing light-weight materials for aircrafts.

The differences from an *environmental* perspective were analyzed according to *energy efficiency* and *pollution*. While HSR vehicles are more efficient in terms of energy consumption, it was highlighted that this comes at the cost of energy previously put into the construction of the HSR infrastructure. In terms of vehicle operations, aircraft machines consume the highest amount of energy. Regarding pollution, the environmental impact of HSR through sulphur dioxide emissions is nearly four times bigger than that of aircraft. In contrast, emitted $\mathrm{NO_x}$ is comparably low. Due to the use of electricity, the carbon footprint of the vehicles along their operating zones is nearly nonexistent compared to the high $\mathrm{CO_2}$ emissions of an air vehicle which is powered with fuel. Assuming that renewable forms of electricity may further advance in the near future, it was concluded in this thesis that HSR is less harmful in terms of pollution than air transport.

With respect to *infrastructure* the focus was put on how HSR and air transport operate their routes and what is needed to conduct a transport itineraries. It was shown in the discussion that there is no clear champion in this category as both infrastructure types are fundamentally different and as such can be seen as solutions to different problems. For example, air transport is organized in a hub-and-spoke network which allows reaching otherwise difficult places (e.g.

oversees) but fails short in providing frequent and quick stops along a route as an HSR can do. In terms of costs, air transport infrastructure benefits from operating on “virtual” rails (sky routes) which do not need to be physically build as it is the case for rails. Also routes can be easily readjusted, which is not possible for a rail system. Therefore, and for other reasons discussed in this thesis, the infrastructure costs are comparably higher for an HSR system.

Finally, the *modal choice* of passengers between air transport and HSR was evaluated and compared based on the most important choice determinants in this field*: price*, *travel duration*, *service frequency* and *reliability*. Moreover *accessibility* was chosen as an additional determinant due to its economic significance. Before the evaluation, an itinerary research was conducted in order to determine comparable routes for the consequent comparison. As shown, prices are in half of the inspected cases in favor of air transport and in the other half in favor of HSR. In terms of “pure” *travel duration*, HSR is inferior to air transport, however, considering the overhead (check-in, boarding, security, connection-flights) generated by air transport, “overall” travel time may be de facto less for HSR. *Service frequency*, is high in Asia for HSR in Europe, however, it strongly depends on the chosen routes and no general advantage exists over air transport. In terms of *reliability* HSR is the leader due to operations being easier to conduct and less complexity, moreover, less delays attributed to passenger-faults. Finally, in terms of accessibility, HSR clearly surpasses air transport since rail stations are located both in urban and suburban areas, while airports are forced to be constructed in rural areas exclusively.

To conclude the main part of this thesis, the topic of *Maglev* was briefly outlined and partially contrasted with the different evaluation criteria previously used to compare HSR and air transportation. It was shown that the technology has certain potential, depending on the further research and development in Japan, however, it cannot be seen as matured competitor to HSR technologies yet.

7.2 Contributions and Implications

In terms of contribution to scholarship, this thesis provides a synthesis of different views on HSR and air transportation. The literature and findings of various authors in this field have been analyzed from different perspectives to provide a more holistic view on the global state of HSR in comparison to air transportation. This work can therefore be used as a basis to further advance in this field and to reason about the strengths and weaknesses of the two systems on a large global scale.

In terms of contributions to practice, politicians and ecologically-responsible investors may refer to the discussion of the environmental impact of HSR and air transport to further advance a clean-energy agenda and reduce CO_2 emissions by investing in HSR infrastructure. Moreover, the points identified in this thesis may support governments in making better decisions when planning to invest in a local HSR infrastructure in terms of risks, shortcomings but also opportunities.

7.3 Limitations and Outlook

As mentioned, this thesis placed its main focus on HSR and its comparison to air transportation. This means, that in several places, certain aspects of HSR have been more thoroughly discussed and explained than aspects of air transportation. For this reason, the reader needs to be aware that some points that are otherwise important in the realm of aviation may have been omitted if they were not relevant for making a comparison with HSR.

In terms of future research it should be noted that the comparison between HSR and air transport was conducted based on certain important aspects. However, due to the scope of this bachelor thesis, certainly not all possible aspects were compared and further research would be needed to continue the comparison based on an extended or a more fine-grained list of criteria.

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Appendix A

Researched Itineraries for Comparisons

The following research was done with the use of several online platforms for the 17th of April 2019. Each itinerary was researched on the 17th of January 2019. Each online platform used for the research is listed below in Table A. The table is arranged after countries in the rows, and the mode of transport on the columns.

Table A Sources for researched itineraries

	High-Speed Rail	Air Transport
China	https://www.chinaticketonline.com http://www.chinatrainguide.com https://www.travelchinaguide.com	https://www.skyscanner.com https://www.google.com/flights https://www.airchina.es/
Japan	http://www.shinkansen.co.jp http://www.hyperdia.com https://www.jrpass.com/	https://www.skyscanner.net https://www.google.com/flights https://www.jal.com/index.html https://www.ana.co.jp/en/us/
USA	https://www.tripplaner.mta.info/ https://www.amtrak.com/home.html	https://www.google.com/flights https://www.skyscanner.net
Germany	https://www.mvg.de https://www.bvg.de https://www.bahn.de/	https://www.swoodoo.com https://www.opodo.de https://google.com/flights
Spain	https://www.renfe.com https://www.aerobusbcn.com/en https://www.tmb.cat/en/barcelona-transport/map/metro	https://www.google.com/flights https://www.skyscanner.net https://www.opodo.de
France	https://en.oui.sncf/en https://www.rhonexpress.fr/en https://www.rome2rio.com	https://www.google.com/flights https://www.skyscanner.net https://www.opodo.de

Appendix B.1

Itinerary Barcelona to Madrid by Air Travel

Time	Location	Mode	Price
08:20	Barcelona Plaza Catalunya		
	|	Aerobus	5.90 €
08:55	Barcelona Airport El Prat		
09:00			
10:00	Barcelona Airport El Prat		
	|		
…	:	Iberia IB1004 (every 11 min)	66 €
11:25	Madrid-Barajas Adolfo Suárez Airport		
12:00	|		
	:	Walk	…
12:10	Alameda de Osuna		
12:28	|		
	:	Metro Line 5	…
12:57	Gran Via		
13:02	|		
	:	Metro Line 1	3 €
13:08	Estacion del Arte		
13:08	|		
	:	Walk	…
13:13	Madrid-Puerta de Atocha		
04:53 h			74.90 €

(a) Travel mode: bus + aircraft + metro

Figure B1 Barcelona to Madrid (air travel)

Appendix B.2

Itinerary Barcelona to Madrid by High-Speed Rail

Time	Location	Mode	Price
08:20			
08:21	Barcelona Plaza Catalunya		
	|	Metro Line 3	2.20 €
08:33	Sants Estacio		
08:33	|		
	:	Walk	…
08:35	Barcelona Sants		
…			
09:00	Barcelona Sants		
	|		
	|		
…	:	AVE - 03092 (every 44 min)	85.10 €
	|		
11:45	Madrid-Puerta de Atocha		
03:25 h			87.30 €

(b) Travel mode: metro + high speed rail

Figure B2 Barcelona to Madrid (high-speed rail)

Appendix C.1

Itinerary Beijing to Shanghai by Air Travel

Time	Location	Mode	Price
08:20	Beijing Capital Times Square	Walk	…
08:30	Xidan		
08:40	|	Metro Line 4	…
	:		
09:00	Xuanwumen		
09:10	|	Metro Line 2	…
	:		
09:40	Dongzhimen		
09:50	|	Metro Airport Line	4 €
	:		
10:00	Beijing Capital International Airport		
10:10	|		
…	:		
11:30	Beijing Capital International Airport	Air China 1557 (every 28.24 min)	180 €
	|		
	:		
	|		
13:40	Shanghai Hongqiao Airport		
13:50			
14:20	Hongqiao Airport Terminal 2	Metro Line 2	1.20 €
	|		
14:47	People's Square		
06:27 h			186.20 €

(a) Travel mode: metro + aircraft

Figure C1 Beijing to Shanghai (air travel)

Appendix C.2

Itinerary Beijing to Shanghai by High-Speed Rail

Time	Location	Mode	Price
08:20	Beijing Capital Times Square	Walk	…
08:30	Xidan		
08:40	Beijing South Railway Station	Metro Line 4	1.20 €
08:50			
09:00	Beijing South Railway Station	High-Speed Rail G1 (every 14.55 min)	82 €
	|		
	|		
	:		
…			
	|		
13:28	Shanghai Hongqiao		
13:40	Hongqiao Airport Terminal 2	Metro Line 2	1.20 €
	|		
14:07	People's Square		
05:47 h			84.30 €

(b) Travel mode: metro + high speed rail

Figure C2 Beijing to Shanghai (high-speed rail)

Appendix D.1

Itinerary Berlin to Munich by Air Travel

Time	Location	Mode	Price
08:20			
08:21	Berlin Central Station		
	|	RB21 Regional Line	…
08:25	S+U Zoologischer Garten		
08:33	|		
	:	Bus X9	2.80 €
08:52	Berlin Airport Tegel		
09:00			
10:00	Berlin Airport Tegel		
	|		
	|		
…	:	Lufthansa LH2033 (every 9.25 min)	110 €
	|		
11:05	Munich International Airport		
11:43	|		
	:	S-Line Metro	11.60 €
12:45	Munich Central Station		
04:25 h			124.40 €

(a) Travel mode: metro + bus + aircraft

Figure D1 Berlin to Munich (air travel)

Appendix D.2

Itinerary Berlin to Munich by High-Speed Rail

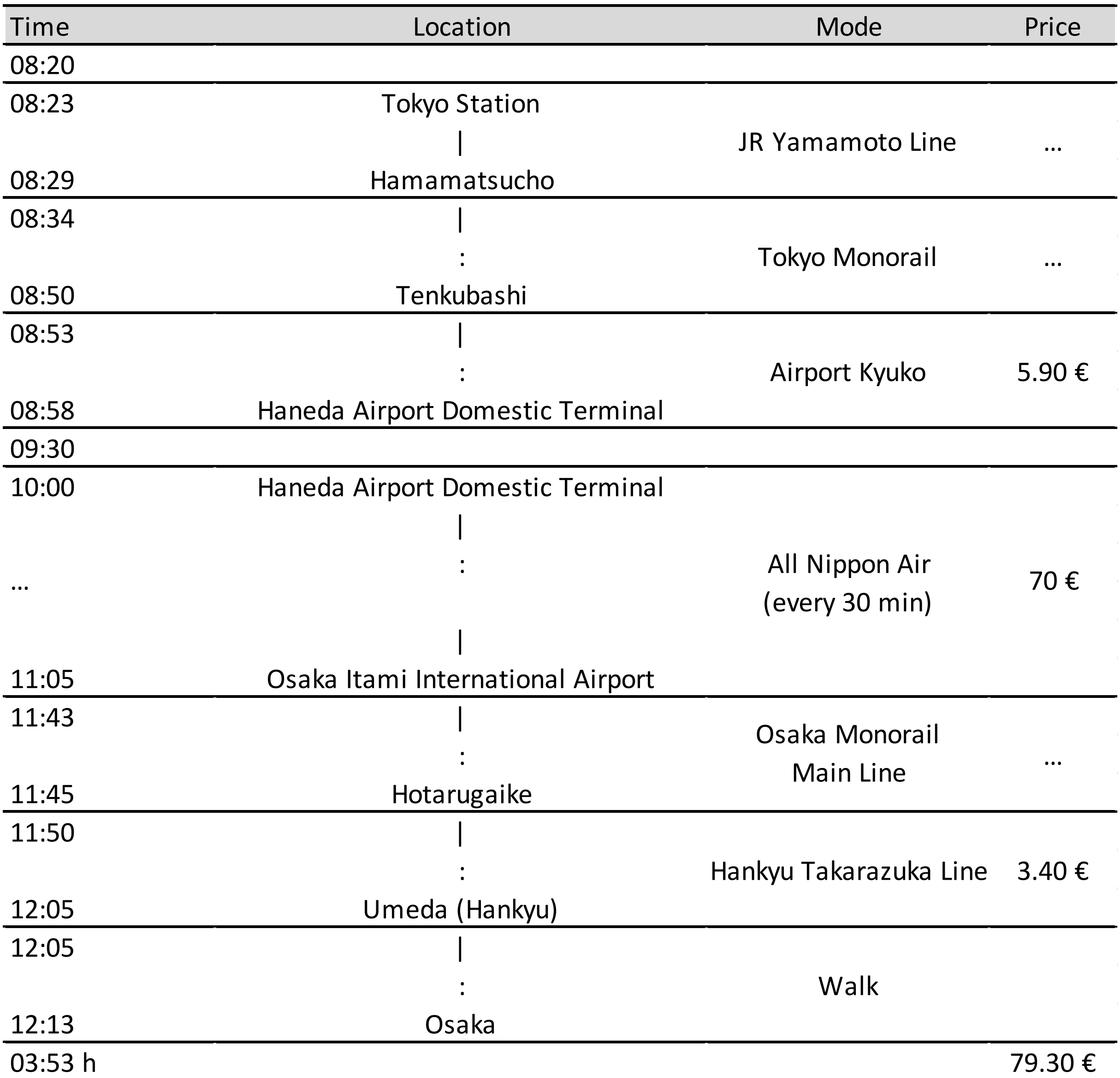
Time	Location	Mode	Price
08:20			
08:21	Barcelona Plaza Catalunya		
	|	Metro Line 3	2.20 €
08:33	Sants Estacio		
08:33	|		
	:	Walk	…
08:35	Barcelona Sants		
…			
09:00	Barcelona Sants		
	|		
	|		
…	:	AVE - 03092 (every 44 min)	85.10 €
	|		
11:45	Madrid-Puerta de Atocha		
03:25 h			87.30 €

(b) Travel mode: metro + high speed rail

Figure D2 Berlin to Munich (high-speed rail)

Appendix E.1

Itinerary Tokyo to Osaka by Air Travel



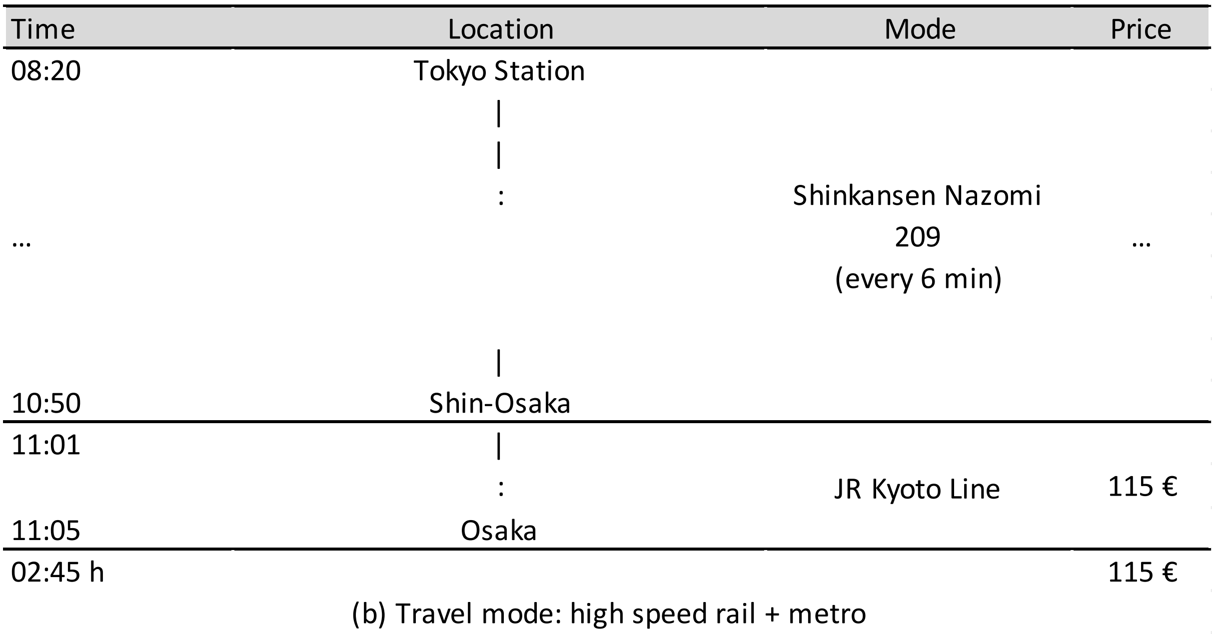
Time	Location	Mode	Price
08:20			
08:23	Tokyo Station		
	|	JR Yamamoto Line	…
08:29	Hamamatsucho		
08:34	|		
	:	Tokyo Monorail	…
08:50	Tenkubashi		
08:53	|		
	:	Airport Kyuko	5.90 €
08:58	Haneda Airport Domestic Terminal		
09:30			
10:00	Haneda Airport Domestic Terminal		
	|		
…	:	All Nippon Air (every 30 min)	70 €
	|		
11:05	Osaka Itami International Airport		
11:43	|	Osaka Monorail Main Line	…
	:		
11:45	Hotarugaike		
11:50	|		
	:	Hankyu Takarazuka Line	3.40 €
12:05	Umeda (Hankyu)		
12:05	|		
	:	Walk	
12:13	Osaka		
03:53 h			79.30 €

(a) Travel mode: metro + aircraft

Figure E1 Tokyo to Osaka (air travel)

Appendix E.2

Itinerary Tokyo to Osaka by High-Speed Rail



Time	Location	Mode	Price
08:20	Tokyo Station		
	|		
	|		
	:	Shinkansen Nazomi	
…		209	…
		(every 6 min)	
	|		
10:50	Shin-Osaka		
11:01	|		
	:	JR Kyoto Line	115 €
11:05	Osaka		
02:45 h			115 €

(b) Travel mode: high speed rail + metro

Figure E2 Tokyo to Osaka (high-speed rail)

Appendix F.1

Itinerary Lyon to Paris by Air Travel

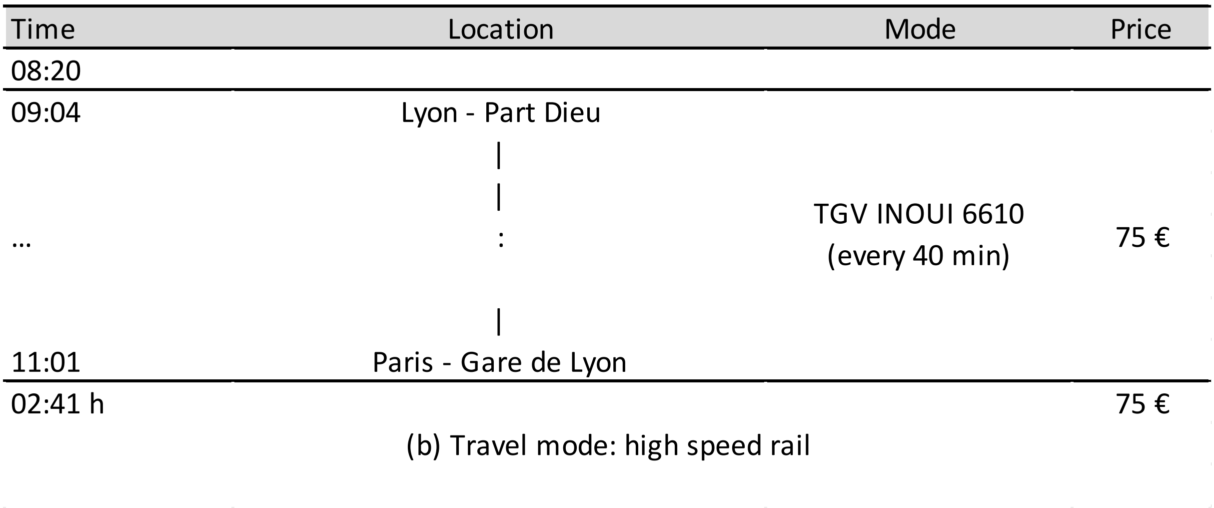
Time	Location	Mode	Price
08:20			
08:30	Lyon - Part Dieu		
	| :	Rhônexpress Bus	15.20 €
08:59	Lyon - Saint Exupery Airport		
09:30			
10:00	Lyon - Saint Exupery Airport		
	| :	British Airways BA361	…
10:45	London Heathrow Airport		
11:00			
13:20	London Heathrow Airport		
	| :	British Airways BA314 (every 19 min)	274 €
15:35	Paris Charles de Gaulle Airport		
16:00			
16:21	Paris CDG Airport Terminal 2		
	| :	Le Bus Direct	18 €
17:05	Paris - Gare de Lyon		
08:45 h			307.20 €

(a) Travel mode: bus + aircraft

Figure F1 Lyon to Paris (air travel)

Appendix F.2

Itinerary Lyon to Paris by High-Speed Rail



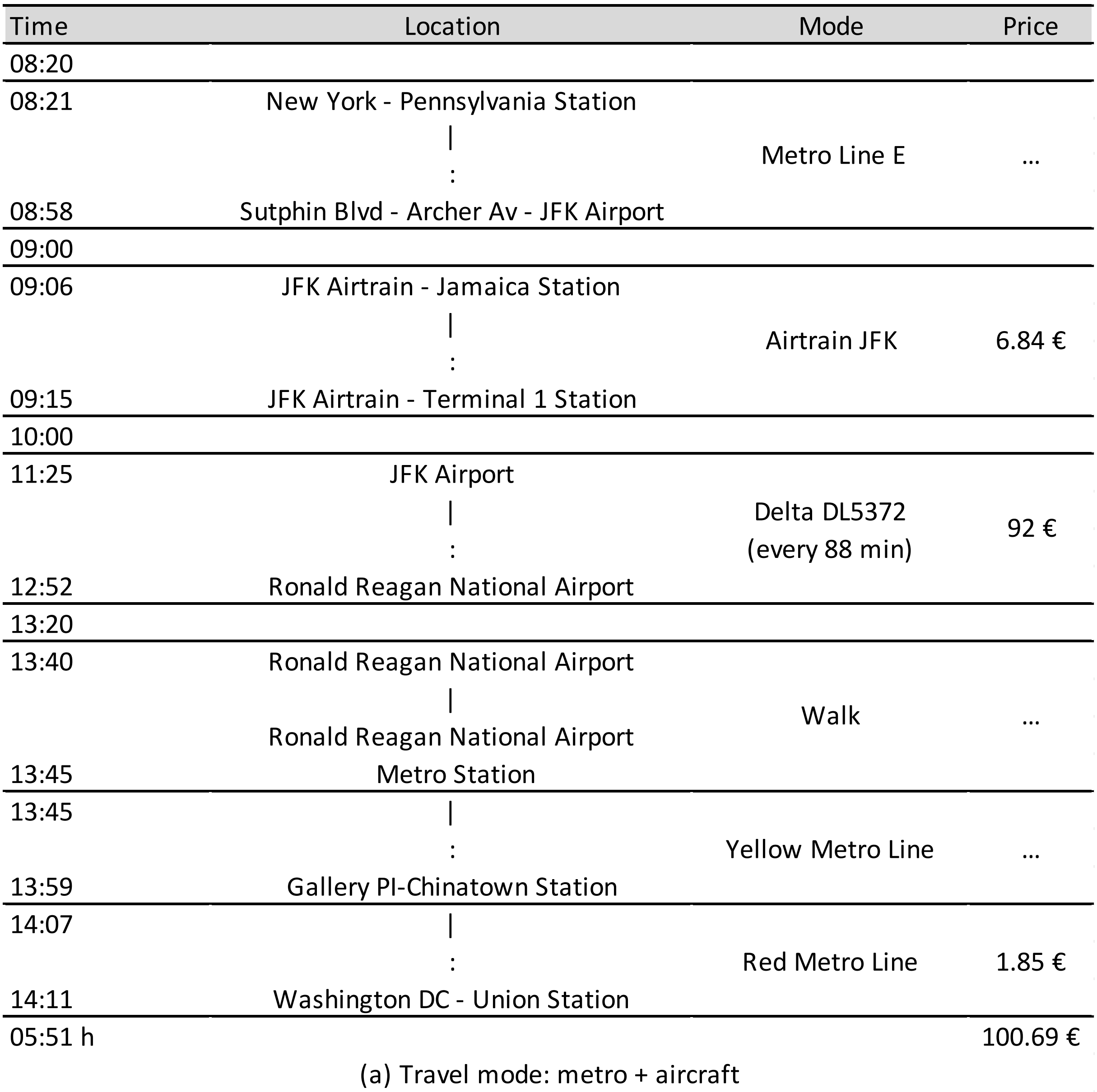
Time	Location	Mode	Price
08:20			
09:04	Lyon - Part Dieu		
	|		
	|		
…	:	TGV INOUI 6610 (every 40 min)	75 €
	|		
11:01	Paris - Gare de Lyon		
02:41 h			75 €

(b) Travel mode: high speed rail

Figure F2 Lyon to Paris (high-speed rail)

Appendix G.1

Itinerary NYC to Washington DC by Air Travel



Time	Location	Mode	Price
08:20			
08:21	New York - Pennsylvania Station	Metro Line E	...
	|		
	:		
08:58	Sutphin Blvd - Archer Av - JFK Airport		
09:00			
09:06	JFK Airtrain - Jamaica Station	Airtrain JFK	6.84 €
	|		
	:		
09:15	JFK Airtrain - Terminal 1 Station		
10:00			
11:25	JFK Airport	Delta DL5372 (every 88 min)	92 €
	|		
	:		
12:52	Ronald Reagan National Airport		
13:20			
13:40	Ronald Reagan National Airport	Walk	...
	|		
	Ronald Reagan National Airport		
13:45	Metro Station		
13:45	|	Yellow Metro Line	...
	:		
13:59	Gallery Pl-Chinatown Station		
14:07	|	Red Metro Line	1.85 €
	:		
14:11	Washington DC - Union Station		
05:51 h			100.69 €

(a) Travel mode: metro + aircraft

Figure G1 New York City to Washington DC (air travel)

Appendix G.2

Itinerary NYC to Washington DC by High-Speed Rail

Time	Location	Mode	Price
08:20			
09:03	New York - Pennsylvania Station		
	|		
	|		
	:	Acela Express 2151 (every 76.5 min)	153 €
	|		
11:59	Washington DC - Union Station		
03:39 h			153 €

(b) Travel mode: high speed rail

Figure G2 New York City to Washington DC (high-speed rail)