Sustainability and Related Factors of High Speed Railways

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Thesis submitted for the fulfilment of the Degree of PhD

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December 2019

Abstract

High-Speed Railways (HSR), which represent a safe and sustainable mode of transportation, provide access and mobility for the society, and support the growth of the economy in addition to creating new jobs, supporting welfare, and promoting local business activities.

This research addresses the shortage of knowledge in evaluating the performance of selected HSR systems and in distinguishing the factors that contribute to the sustainable performance of HSRs. The aim of this study is to evaluate the sustainability of selected HSRs and identify factors that affect such sustainability. The objectives of this research are to evaluate productivity, technical and technological efficiency of the selected HSRs, define the factors that can affect productivity and efficiency scores and make suggestions for improving the sustainability of HSRs.

The secondary data methodology has been used, supported by empirical evidence. Most of the data was gathered from the Internet, research in depth of the high-speed railways in the selected countries, and International Union of Railway's websites in addition to analysing railway statistics and data from European and institutional publications. This includes the use of a multi-stage approach of applying three specialised software packages, namely, NVivo, DEA, and ISM SPSS.

The main findings show that HSRs in Asia has higher productivity and higher efficiency scores than that of HSRs in Europe. The research found that the key factors among all the identified factors that affected the productivity and efficiency of HSRs are; density of population, average traction power of HSR trains, average time that passengers spend on trains and average distance that passengers travel on the HSR.

The findings of this research can help develop strategic guidelines to improve the performance and, by the result, the sustainability of HSRs. The recommendations are drawn for more research expansion, including the consideration of other HSRs, particularly their best practices.

Keywords: High-Speed Railway, Sustainability Factors, Efficiency, Productivity

Declaration

This is to declare that the research and findings reported here are of my own work and that they are not submitted to any other university or learning institution.

Signature: *Inara Watson*

Date: 24/12/2019

Acknowledgement

The time that I spent working on this research was the most enjoyable in my long study. This research has widened my knowledge in High-Speed Railway systems and facilitated me to share my knowledge and experience in railways with the wider scientific community.

My supervisor and Director of my PhD Studies, Dr Amer Ali, has been supportive, encouraging, and gracious throughout the years of my study. My second supervisor, Dr Ali Bayyati, has been helpful and cooperative. I would very much like to thank Dr A. Ali and Dr A. Bayyati for the time that they spent to help me in this journey. I would like to thank Professor Ali Emrouznejad for his help and support for using DEA software.

Further thanks go to all staff of the School of Built Environment and Architecture for their patience and help. Also, I would like to thank staff of Railisa UIC Statistics for their support and guidance and help with data, which I used for this research.

Finally, I must thank my husband David who has been my saviour through this journey and without his help this research would not be possible to do.

Contents

Abbreviations

Abbreviation	Meaning
AC	Alternating Current
ATENDO	Attention and Assistance
ATP	Automatic Train Protection
ATC	Automatic Train Supervision
AVE	(Spanish) Alta Velocidad Española
BC	(Productivity) Boundary Change
BCC	Banker, Chames, Cooper
CAF	(Spanish) Construcciones Y Auxiliar de Ferrocarriles
CCR	Chames, Cooper, Rhodes
CH	HSR in China
CMI	Circular Malmquist Index
CNR	China North Railway
CRS	Constant Returns to Scale
CSR	China South Railway
CTCS	Chinese Train Control System
DB	(German) Deutsche Bahn
DC	Direct Current
DE	HSR in Germany
DEA	Data Envelopment Analysis
DMU	Decision-Making Units
DRS	Decreasing Returns to Scale
GDP	Gross Domestic Product
GHG	Greenhouse Gas (Emissions)
GSM-R	Global System for Mobile Communications-Railways
GTR	Govia Thamslink Railway
EC	(Technical) Efficiency Change
EMU	Electric-Multiple Unit

ERA	Environmental Risk Assessment
ERF	Energy Recovery Factor
ERMS	Electronic Records Management System
ERTMS	European Rail Traffic Management System
ES	HSR in Spain
ETCS	European Traffic Control System
EU	Europe Union
FR	HSR in France
HS	High Speed
HSR	High-Speed Railway
HSRS	High Speed Rolling Stock
ICE	Inter City Express
IPCC	International Panel on Climate Change
IRS	Increasing Returns to Scale
IT	HSR in Italy
JR	HSR in Japan
KTX	Korea Train eXpress
KR	HSR in South Korea
LZB	(German) Linienzugbeinflussung
MI	Malmquist Index
MRF	Material Recovery Factor
NDEA	Network Data Envelopment Analysis
NL	HSR in The Netherlands
NTV	(Italian) Nuovo Transporto Viaggiaton
NVivo	A qualitative data analysis software
OBB	(German) Osterreichische Bundesbahn,
OTE	Overall Technical Efficiency
OTIE	Overall Technical Inefficiency
PPS	Production Possibility Set
PTE	Pure Technical Efficiency

PTIE	Pure Technical Efficiency
PZB	(German) Punktuelle Zugbeeinflussung
RENFE	(Spanish) Red Nacional de Ferrocarriles Españoles
RS	Rolling Stock
RTS	Returns to Scale
SBB	(German) Schweizerische Bundesbahn,
SD	Standard Deviation
SE	Scale Efficiency
SIE	Scale Inefficiency
SEF	Service Effectiveness
SNCF	(French) Societe Nationale des Chemins de fer
IBM SPSS	Statistical Package for the Social Sciences
TAMP	Track Analysis and Maintenance Planning
TCDD	(Turkish) Türkiye Cumhuriyeti Devlet Demiryollari
TE	Technical Efficiency
TEF	Technical Effectiveness
TPF	Total Productivity Factor
TGV	(French) Train a Grande Vitesse
THSR	Taiwan High-Speed Rail
TR	HSR in Turkey
TSI	Technical Specification for Interoperability
TW	HSR in Taiwan
TVM	(French) Trammission Voie Machine
UIC	(French) Union Internationale des Chemins
UK	United Kingdom
USA	United States of America
VRS	Variable Returns-to-Scale
ZUB	(German) Zugbeeinflussung

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Introduction

1.1 Background

High-Speed Railway (HSR) systems continue to expand worldwide and gain more reputation as one of the most safe, effective, and sustainable mode of transportation (Ali, 2014). The world economy faces important changes. Increasing globalization may have large impacts on the transport system. The environmental problems faced by the transport sector, especially the emission of greenhouse gasses, are a major concern. Transport delivers a huge contribution to rising greenhouse gas emissions, brings a threat to biodiversity and human health. Current transport problems harm humans and the environment.

The International Panel on Climate Change (IPCC) has predicted that if nations around the world will not reduce the production of CO_2 emissions, then temperature will rise between 3.7-4.8 degree Celsius above the current level by 2100 (Ipcc.ch., 2019). Transport produces around 23% of global CO_2 emissions, and it will increase by 1.7% by 2030. Most of this pollution comes from road transport, as railways are responsible for only 2% of total transport emissions (UIC, CER., 2015).

Railway transport is becoming an important mode of transportation because it offers many advantages compared to other modes of transport, whilst the role of railway transport will continue increasing. Travelling by train, passengers can work, have a rest, eat, or just enjoy the countryside’s views. Railway transport is much greener than road transport or air transport, but this is only for trains powered by electricity (UIC, CER., 2015).

By 2019, sixteen countries worldwide have developed HSR systems with 41,820 km of high-speed lines globally in operation and with another 15,066 km under construction in 20 different countries (UIC, 2019a). China is the leader in the construction of HSR with 26,869 km in operation and 10,738 under construction (UIC, 2019).

The HSR gives the ability to arrive only a few minutes before departure by car, tube, bus, metro or on foot compared to airports where passengers need to arrive with enough time before the flight. Also, a need to take into consideration that airports are always located away from city centres, it takes longer to get there than to a railway station. Trains are also more reliable, safer, and more energy efficient.

1.2 Motivations of study

With future increases in oil prices, the current environmental issues, and aging of populations, governments are looking in the direction for more sustainable and efficient transport. The HSR can bring social benefit and economical profitability. Many countries around the world are working to implement high-speed train services and they have different levels of achievement. There are some drawbacks to the development of HSR, and one of them would be, HSR continuously needs huge taxpayer subsidies. Also, some research shows that only 20% of high-speed train commuters come from other modes of transport, but 80% move from a low speed railway to a high-speed railway (Jehanno et al., 2011). Most of existing HSRs are not profitable (Bodman, 2019).

For this reason, it is needed to benchmark the performance of existing HSRs to indicate the difference in performance and find the factors that can influence this performance. It is difficult to compare performance of HSRs as they apply different technologies, located in different topographic locations, and serve different sizes of population. The HSRs were developed in different countries at different times and standards. Current research does not benchmark the performance of existing HSRs. Mostly, it only compares the performance of HSR against air or road transport.

The main motivations of this study are:

- Awareness concerning climate change and scarcity of natural resources.
- Interest in railway transport and the benefits that it may bring for society.
- Under-researched area and shortage of knowledge in:
    a) Evaluating the level of performance of different HSRs worldwide.
    b) Identifying the key factors that influence the performance of HSRs and how to improve such performance particularly the sustainability of HSRs.

This research addresses the lack of knowledge in the benchmarking and the evaluation of the efficiency and productivity of selected HSR systems and in the identification of the factors that contribute to the sustainable performance of HSRs.

1.3 Research questions

The main research questions are:

- What are the main features of the HSR concept?
- Which technical design aspects of HSR concepts are more sustainable compared to conventional railway concepts and in which way?
- What are the specific conditions of HSR in Europe, Asia, and the USA regarding economic, environmental, and social sustainability?
- What is the individual-level Technical Efficiency (TE) for each of the selected HSRs using the two models of DEA CCR and BCC?
- What is the correlation between the TE of the selected HSRs and the factors that affect it?
- What are the main factors that affect the sustainability of selected HSRs?

To answer these questions, it is necessary to define HSR and give an overview of the main features of the HSRs and their positive and negative points. It is also important to analyse the HSR systems in developed and developing countries particularly those with emerging strong economies emerging countries to establish the advantages and disadvantages of the construction of HSR in these countries. These are in addition to analysing the differences in building and operating the different HSR systems.

1.4 The aim and objectives of the research

The main aim of this research is to investigate how HSR systems can be sustainable to align with the proposed HSR concept and the planned future expansion of the HSR concept worldwide. The PhD research aims to identify the HSRs that have higher productivity and higher technical efficiency and factors that influenced the performance of these HSRs. Possible measures to improve the sustainability of HSR are proposedly based on their unique conditions.

The HSR systems will be assessed based on a specific group of criteria to define what makes some of them more efficient than another. Also, this research will establish the importance of HSR in comparison to other mass transportation modes in terms of external costs that society must pay. Analyse the factors that affect the economic environmental and social sustainability of selected HSRs.

The research also aims to establish a more sustainable way of developing and operating HSR. The economic and demographic growth, a finite number of natural resources, and global climate change induce HSR for intrusion in new markets. Most of the world industries were built when oil prices were cheaper than now. The future of transportation lies in the efficient use of natural resources. Differences in the amount of natural resources that are needed for different transportation modes will be investigated.

The objectives of this research are:

- To evaluate the productivity, technical and technological efficiency of the selected HSRs.
- To establish targets and potential improvements for the selected HSRs.
- To define the factors that can affect productivity and efficiency scores.
- To make suggestions for improving the sustainability of HSRs.

1.5 Definition of HSR

The HSR is defined as a high-speed railway system that contains the infrastructure and the rolling stock. The infrastructure can be new build dedicated lines enabled for trains to travel with speed above 250kph or upgraded conventional lines with a speed up to 200 or even 220kph (Jehanno et al., 2011). HSR requires special built trains with increased power to weight ratio and must have an in-cab signalling system as traditional signalling systems are incapable above 220kph (Jehanno et al., 2011). This is the definition of HSR that was given by UIC, but in different countries it may differ from this, as speed is not the best index. For example, in the USA, HSR is divided into three groups: emerging rail with speeds 90 to 110mph (145 to 177kph), regional rail of 110 to 150mph (177 to 241kph), and express rail with a speed of 150mph (241kph) and above (Reason.org., 2019). In Japan, Shinkansen, is defined as HSR, where trains run over 200kph along most of the line (Uic.org., 2018). There are some differences in operational and commercial speed. Also, often commercial speeds are much lower than the operational ones. The reason for this can be that the speed is limited for safety reasons and trains use parts of the conventional line or too many stops.

The first dedicated HSR was developed in Japan in 1964, and it took only five years to build the 515-km of the Tokaido Shinkansen (Japanese Railway Technology Today, 2001). In 2018 there was 41,820km of HSR worldwide; 31,875 in Asia, 9,211km in Europe and 735 km in the USA. The HSR network is expanding rapidly with 15,066km is under construction and another 30,546km is planned (UIC, 2019a). The HSR network is getting wider as more countries are introducing this service. In the Middle East, two countries are developing HSR, Saudi Arabia and Morocco (UIC, 2019a).

The first country in Europe that started to develop HSR was Italy. The Roma-Firenze line development started in 1970 and was partially opened in 1977 but fully completed much later (Dumas.ccsd.cnrs.fr., 2019). The first completed HSR line in Europe was from Paris to Lyon and opened in 1981 where trains operate with a speed of 260km/h (UIC, 2019b). Other countries such as Germany, Spain, Italy, and UK followed it so that by 2018 there was 9,211km of HSR lines in Europe, whilst now 10 countries in the EU have developed HSR lines (UIC, 2019a).

The most significant HSR network was built in China. In the last 10 years, they have built 26,869km of HSR lines and 10,738km is under construction (Uic.org., 2018). In different countries there were different reasons behind decisions to build HSR, from an increase of capacity as it was in France to promote their country, as it was in Spain with Madrid-Seville line or to connect the labour market with natural resources as the case in China, or maybe for defence purposes such as the case in Baltic countries. HSR systems were divided into four groups depending on their relationship with conventional rail (Reason.org. 2019); dedicated line, mixed high-speed line, mixed conventional line and fully mixed. Each of these types of HSR has some advantages and disadvantages.

Dedicated HSR represents a line which is fully separated from a conventional line, has a high capacity, high safety, and no level crossings. The line has fences all along the line, often built on viaducts or in long tunnels and has a high construction cost, such as the case in Japan and Taiwan.

Mixed HSR lines have a wider area to serve, increased accessibility as high-speed trains run on dedicated and conventional lines, high capacity of HS lines stretches over larger areas, reduced building costs. HSR trains can use conventional rails in city centres in areas where land is more expensive to build dedicated lines. However, stretches of conventional line have less capacity and can be a bottleneck for increased traffic, reduces the safety, increases the maintenance costs whilst the rolling stock must be equipped with two signalling systems for HSR and conventional rail, such as the case in France.

Mixed conventional rail represents lines that are used by HSR trains and by conventional trains. Mixed traffic reduces the capacity of the line because of big differences in the speed of trains and it also reduces safety. It can be a good solution if a country has a different gauge from the standard gauge size to be part of the European railway network and supports interoperability of international services, such as the case in Spain. This type is more difficult and expensive to maintain, needs special rolling stock, which is also more expensive to purchase and maintain.

Fully mixed lines represent lines used by all types of trains including freight, have maximum flexibility to be used to full capacity, reduce the safety, reliability, punctuality and increase maintenance costs. An example of such lines is those used in Germany. Table 1.1 shows the different HSR technologies in the selected countries.

Table 1.1 High-Speed Rail technologies in the selected countries (Source: Core.ac.uk, 2019)

Country	**Japan**	**France**	**Germany**	**Italy**	**Spain**	**Korea**
Line	Tokyo-Osaka	Paris-Lyon	Hannover-Wurzburg	Roma-Paris	Madrid-Barcelona	Seoul-Pusan
Length of line in km	515	427	327	260	522	412
Max. speed (kph)	260/300	300	250	250	300	250
Travel time	2h 30min	1h 50min	2h	1h 35min	2h 30min	1h 55min
Radius of curvature R_{min} (m)	2500	4000	7000	3000	4000	7000
Max. longitudinal gradient (%)	20	35	12.5	8	30	35
Distance of axes of two tracks (m)	4.2	4.2	4.5	4.2	N/A	5.0
Superelevation (mm)	200	180	150	160	N/A	N/A

All HSRs must have advanced signalling systems and automated train control systems. Another common thing for all HSRs is that they are very expensive to build and only two of them recovered construction costs (Core, 2019).

Rolling Stock is another part of the HSR systems. High-speed trains that are presented in Table 1.2 have a large variety in axle loading ranging from 11.4t for Hitachi train to 23t axle loading for Bombardier and Acela Express. This large difference can be explained by the type of railway that uses this rolling stock. The Shinkansen line that uses Shinkansen-Series 700 is fenced throughout to secure the entire length of the track. In contrast to these, the Acela Express operates on an upgraded line with level crossings. Amtrak trains are equipped with an anti-collision structure to meet USA crash standards. Zefiro, high-speed trains manufactured by Bombardier is one of the most efficient and advanced trains in the world (UIC, 2018a).

Table 1.2 Comparison of different high-speed trains in terms of power systems, axle loading, and car body materials (Source: Watson et al.,2017c)

Country	**Main Constructor**	**Train**	**Power system**	**Axle Loads**	**Car Body**
France	Alston	AGV	Centralized	17t	Aluminium with Carbon
Japan	Hitachi	Shinkansen-Series 0	Distributed	16t	Carbon steel
Japan	Hitachi	Shinkansen-Series 700	Distributed	11.4t	Aluminum alloy
Spain	Talgo	Talgo 350	Centralized	17t	Aluminium
Italy	Hitachi Rail Italy	Frecciarossa	Distributed	17t	Aluminum alloy
Germany	Siemens	ICE1	Centralized	19.5	Aluminium-Silicon alloy
Germany	Siemens	ICE2	Centralized	19.5t	Aluminium-Silicon alloy
Germany	Siemens	ICE3	Distributed	15t	Aluminium
Sweden	Bombardier	SJ X2	Centralized	17.5t	Stainless steel
USA	Bombardier	Acela Express	Centralized	23t	Stainless steel
China	Bombardier	CRH1	Distributed	15t	Stainless steel
China	Siemens	CRH3C	Distributed	17t	Aluminium
Canada	Bombardier	Zefiro	Distributed	16.5t	Aluminium

1.6 Differences between HSR and conventional rail

The fundamental principle is the same, but the biggest difference lies within speed and capacity. To increase the capacity of the line, it is very important that trains that operate on the line must not have a big difference in operational speeds.

HSR and conventional rail have the following technological differences:

- In track quality: HSR requires a specific design, higher standards of surface, welded rails, and a different and more advanced signalling system. Most HSRs are built on slab track (Jehanno et al., 2011). HSR has a larger curve radius than conventional rail. For a speed of 300kph the minimum radius is 4000m, grades of 3.5% rather than 1-1.5% for existing lines with mixed traffic (edoc.pub., 2019). HSR track is protected by fences from wild and farm animals. HSR lines do not have any level crossings and have fewer stops than conventional lines.
- In traction power: For higher speeds, there is a need to have a more powerful rolling stock.
- In signalling system: When the speed of the HSR is above 220kph, the traditional signalling systems become inefficient (Jehanno et al., 2011). HSR trains require in-cab signalling systems.
- In power supply: HSR needs at least 25kV but conventional rail voltage can be lower.

1.7 Structure of the thesis

This thesis is structured in the following way. Chapter 2 reports an extensive review of the development and issues concerning the HSR systems together with related recent research and publications. Chapter 2 presents the methodology used to analyse the efficiency and productivity of transport modes. The methodology used to complete this research project is presented in Chapter 3. Chapter 4 reports the analysis of the existing HSR systems in selected countries. The main issues relating to the sustainability of HSR are discussed in Chapter 5. Chapter 6 shows the selected data and related aspects. Chapter 7 reports the main findings and results concerning the sustainability and related factors of HSR systems. The analysis and discussion of the main findings are shown in Chapter 8, whilst Chapter 9 reports the key conclusions and recommendations for future work.

Chapter 2

Literature Review

2.1 Introduction

Transport can be classified by the following modes: road, rail, sea, and air; by a system of management: private or public and are through application: local, regional, and long distance. Traffic growth is largely the result of economic growth. Personal travel increases by a factor 1.5 in relation to the GDP. Sustainability cannot be achieved on the basis that everyone on average driving and flying 6% more kilometres year on year without limit (Whitelegg & Haq, 2003). Railway transport is becoming an important mode of transportation. HSR allows to move passengers over long distances in a shorter time. HSR can help to reduce the amount of pollution from transport and reduce congestion on roads. It is safe, fast and a comfortable way to travel.

2.2 Evaluation of the sustainability of railway transport

Back in the 1990s European Conference of Ministers of Transport emphasized that apart from benefits that transport can bring, there are some negative effects brought by transport at present. The negative effects include accidents, congestion, air and noise pollution, energy, land, and other natural resources consumption to produce vehicles and infrastructures (European conference of ministers of transport, 1998). The balance of the benefits and negative effects that transport brings was investigated in several studies. The economy cannot grow sustainably if society continues to use natural resources and produce pollution at the same speed. Technology and behaviour of people must be changed. The cost of travel will have to rise to reflect the damage done to health and the environment.

To be sustainable it was estimated that a global population on average must produce no more than 2.0 tonnes CO_2 per person but currently it is around 4.0 tonnes per person (Banister, 2005). In 2011, UIC published a report “High Speed Rail and Sustainability” where it shows that HSR is the most environmentally friendly mass transportation mode. Even taking into consideration externalities that will be produced by construction of infrastructure and rolling stock. Sustainability for railway companies “means to meet the expectation of society and customers and sustain business by responsible leadership" (Jehanno et al., 2011).

Tan et al., (2016) studied the sustainability strategy of China's HSRs. In China, by 2020, the total railway network will reach 120,000km, and by 2025 the HSRs network will be 38,000km. With a rapid increase in the length of HSRs in China, there are needs to look for new technologies that will increase the sustainability of existing lines. The authors investigated areas that must be covered in the future to improve HSR technologies, such as, freight transportation by HSRs, HSR driverless technology, improving the monitoring and diagnostic of HSR technology, developing a new generation of HSR equipment and rolling stock, etc.

Chen, (2013) conducted research on sustainability analysis of Wuhan-Guangzhou HSR in China. Research concentrated on the analyses of efficiency and direct and indirect transportation impact of developing HSR. It was found that HSR shrinks time and space along the line, increases the capacity and improves the accessibility along the corridor, but cities that are not connected to HSR will have a decline in accessibility. To increase HSR ridership in China, they just cancel conventional trains, and this had a very negative impact on low-income commuters. This is one reason to doubt the sustainability of HSRs in China.

Vardar et al., (2016) studied the relationship of transportation with urbanization and the influence of transportation on society. With increasing the economic growth increasing the mobility of population, but this on the other hand increased the pressure on the environment and sustainable spatial development. The authors highlight the importance of HSR as a transport mode, which supports the increasing capacity of railway lines, provides fast journeys, and increases accessibility. Increasing investments in HSR in Europe will increase the competition of HSR with airlines. The authors summarised the development of selected HSR systems in Europe and Asia.

The sustainability development of HSR and airlines from the perspective of passenger mode choice analysed by Su et al., (2019). This research analysed passenger flow and mode choice behaviour in the Beijing-Shanghai corridor. They found that factors that affect the choice of transport mode are income, access time, gender, and age of passengers. The authors suggested that to increase number of passenger travel by HSR need to adopt differential pricing between peak and off-peak time and provide discounted joint tickets. Facilities at HS railway stations must be more female and business travel welcome.

Chang et al., (2018) evaluated the sustainability of HSR construction projects. The authors established 45 indices for sustainability evaluation. They applied selected indices to evaluate the sustainability of the Harbin-Dalian Passenger Dedicated Line. It was found that the overall project has a lack of investment control, the budget of the project was underestimated, investment and financial risk have a lack of control. It was found that the project has a lack of noise and electromagnetic radiation reduction measures. However, the project will increase capacity of railways, reduce the travel time, and create new jobs. However, with implementing the suggestions that authors proposed, such as installed noise barriers along the route, building the tunnel in urban areas will be substantial changes in cost- benefit analysis and economic benefits will be dramatically reduced.

With the increasing temperature, increasing pollution and amount of natural resources that is used globally, increases the role of the sustainable development and circular economy. Liu et al., (2019) studied the potential of sustainable development and the circular economy for the development of HSR stations and surrounding areas. In China, construction works produce one-third of the total pollution, 45% of waste and nearly half of the total CO_2 emissions. The authors suggested that to reduce waste and pollution from construction of large infrastructure projects it needs that central government must produce a clearer policy guidance to local authorities how to navigate towards sustainability and circular economy. The authors raised a very topical issue reducing the waste from construction than is essential for every project in every country.

Chang et al., (2019) calculated the energy use and environmental pollution caused by HSR transportation in China using a bottom-up modelling approach. The study case was the Beijing-Shijiazhuang HSR line. Chang et al., found that most of the CO_2 or 79% of the total embodied energy of this line was produced by building bridges and tunnels, followed by the track 9% and subgrade 6%. To recover the embodied energy, the future level of capacity is crucial. With the increasing number of electric vehicles, the current gap of 6gr of CO_2 per passenger-km is not enough to classify HSR as green. There is a need from government to propose policies to encourage people to use HSR. Another option is to use HSR lines not only for passengers but also for freight transportation. However, all these proposals do not look enough as energy that powered HSRs in China is mostly produced by coal-powered stations.

There are a substantial number of researchers that investigated the development of HSRs in countries where before HSR did not exist. They compared the benefits and disadvantages of the development of HSR. Katz-Rosene, (2016) investigated the benefits and disadvantages of building HSR in Canada. The author focused on Canada as a case study. The author highlighted that there is a huge variety of views on developing the HSR system. The author studied three ways of investment in developing HSR in Canada public investment, developing HSR through a public-private partnership and fully relying only on private investments. The author admitted that most times the evaluation of the benefits of HSR is largely influenced by the socio-ecological and political-economic views of stakeholders.

Brunello et al., (2006) studied the sustainability problems in transportation and proposed an alternative approach for Australia. The number of stations for HSR must be as less than possible to reduce time for braking, stopping, and acceleration. The second problem that faces HSR is the huge cost that is involved in developing HSR and usually exceeds government funding capacity. The majority of HSRs need government subsidies, and one way to increase it will be to allow freight trains to use HSR lines. This will raise more problems, decrease the capacity of the line, increase maintenance costs, and raise safety issues.

Kamga & Yazici, (2014) investigated the advantages of building HSRs in the USA to create a more sustainable multimodal transport system. The authors summarise the high environmental cost of car and air travel in the USA and highlight high potential that HSR has in the USA as the largest market in the world. HSRs are not only greener than a car or airplanes but also more resistant to extreme weather events. HSR can be the backbone for the transport system and provide an intercity option that will satisfy changes in travel behaviour tendencies.

Guirao & Campa investigated ways to assess sustainability for investment in developing new HSR lines. The authors studied methodologies to select suitable corridors for HSRs lines on the example of Spain. Many HSRs worldwide did not reach predicted ridership and as a result not profitable. The authors highlight that for more accurate traffic forecasting, it is important to identify predominate economic activities along the selected corridor, as this will have an influence on ridership. The cities in a radius of 200 km from the centre must be evaluated differently from the rest of a corridor as they have a big potential to supply many commuters. Also, the authors highlight the role of station location on the future performance of HSR.

There are many researchers that cover different aspects of the sustainability of HSRs. Some of them compare HSRs with airlines and road transport, some investigated future development of HSRs in countries where HSR did not exist. However, it was found only one paper benchmarked the performance of eight selected HSRs. The ten sustainable development principles for railways was published in 2016 by RSSB. They reflect the challenges and opportunities that the railway industry can bring for society without compromising future quality of life (Rssb.co.uk, 2019). These principals cover the economic, environmental, and social sustainability of railways. Despite having the same principles all HSRs perform differently. Some of them are more successful than others.

2.3 Analytic Methods-Data Envelopment Analysis (DEA) approach

To benchmark the performance of HSRs, two approaches have been used. These are Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis. Emrouznejab et al., (2018) produced a bibliography of articles related to DEA which have been published since 1978. They found that in the last three years, interest in DEA methodology had grown rapidly and reached approximately 1000 articles published every year. A full list of the papers concerning the investigation of efficiency and productivity of transport, which are studied in this research is shown in Appendix D.

Growitsch et al., (2009) analysed 54 railway companies using DEA to find out how regulatory environment affects the economic performance of European Railways. Amiril et al., (2014) found that there are 27 sustainability factors that cover the performance of transportation infrastructure projects. They can be divided into environmental, economic, social, engineering/resource utilization and project management performance factors.

Efficiency and effectiveness in railway performance applying a DEA model studied Yu et al., (2008). They selected 20 railways for the year 2002. Because they selected only one year, the results can be influenced by external causes that are not under railway control. The productivity growth in European railways was studied by Loizides et al., (2002). They investigated 10 railroads of the EU from 1970 to 1992. It was found that technical changes declining over time and only German and British railways have a positive technical change. Regarding the DEA approach, only one research has been found that compares the sustainability of HSRs. Doomernik, (2014) the benchmark of performance of eight HSRs between 2007 and 2012. The author investigated production efficiency and service efficiency and identified the most efficient high-speed railway systems. A substantial difference in performance was found between railways in Asia and Europe and a huge difference within these regions.

Data Envelopment Analysis (DEA) is a method that measures the efficiency of similar Decision-Making Units (DMUs) (Emrouznejad et al., 2011). The DEA is a non-parametric method based on the assumption that the production function of fully efficient DMUs is not known (Bray et al., 2017). The DEA was proposed in 1978 by Charnes, Cooper and Rhodes. This method is more appropriate for evaluating efficiency of HSRs as input values do not vary substantially over time (Graham, 2008). In this research, HSRs are Decision-Making Units. The DEA defines the relationship between the outputs that the HSRs can produce and the inputs and aims to estimate the relative efficiencies of HSRs. Cook et al., (2013) concluded that the number of DMUs must be at least twice the number of inputs and outputs combined.

This DEA analysis has been acknowledged before to benchmark the performance of decision-making units (DMU) and found the best practice. The efficiency of DMUs depends on their distance to the frontier. This methodology uses the ratios between outputs and inputs and compares all units and their relative efficiency with respect to the best performing unit. The efficiency score (1) for units is defined as the weighted sum of multiple outputs, $\sum_{k=1}^{r} UkYkj$ divided by the weighted sum of multiple inputs $\sum_{i=1}^{m} ViXij$ (Charnes et al., 1978).

$$max\ h_j = \frac{\sum_{k=1}^{r} UkYkj}{\sum_{i=1}^{m} ViXij} \quad (1)$$

Where:

h_j, is the maximum ratio of outputs to inputs,

k=1…. r is the sum of k-th positive output and

i=1…m is the weight i-th positive inputs.

The function that presents maximum output achieved from a given level of input call output-oriented function. Figure 2.1 shows the efficient production frontier.

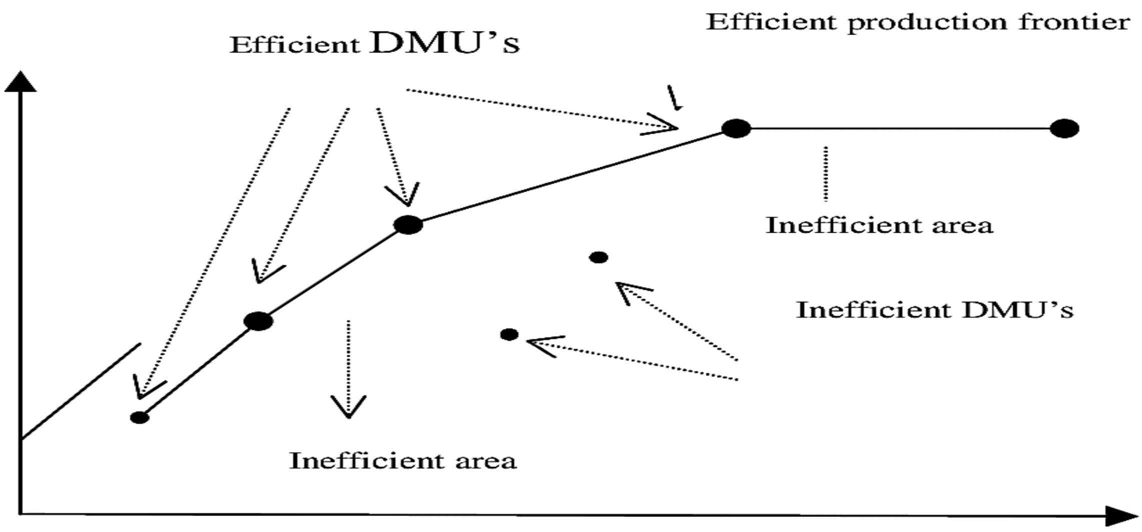

Figure 2.1 DEA production frontier (Barros & Perrigot, 2020)

One advantage of applying DEA is that it can operate with multiple inputs and outputs, and it is not needed to clarify their importance. Other advantages are that it is suitable for small samples and has a small run time (Nataraja et al., 2011). The DEA compares each HSR with all other HSRs and identifies HSRs that are operating inefficiently and find the target values of output and input for inefficient HSRs. The DEA technical efficiency and service effectiveness study for railways was carried out (Yu, 2008) but environmental sustainability was only classified as influencing factors.

2.3.1 CCR and BCC DEA models

Cavaignac et al., (2017) concluded that only around 8% of the total number of articles that use DEA in transport analysis analyses railway transport. More than half of all articles using DEA in transport analysis used Constant Return to Scale

(CCR) and Variable Return to Scale (BCC) approach and the second most popular is the two-stage DEA method when on the second stage Tobit regression analysis is used. Tobit regression was used at the final stage of DEA to evaluate the relationship between related factors and a variety of results.

The CCR model is named after its developers Charnes, Cooper and Rhodes (1978) and BCC model is named after Banker, Charnes and Cooper (1984). The CCR model assumes of constant returns-to-scale (CRS) and the BCC model assumes of variable returns-to-scale (VRS) (Yu et al., 2010). The CRS model assumes that if you increase the inputs, outputs will increase proportionally. In the single input-output model, the efficiency frontier will be a straight line. The CRS model is an ideal version, but often the performance of DMUs can be affected by reasons beyond managerial control, such as economic crisis, changes in population, etc. The VRS model assumes that with increases in the inputs, it does not result in proportional changes in the outputs.

The efficiency is defined as a ratio of outputs to inputs, and this ratio must be equal or less than 1. If the ratio is equal to 1, it points to the most efficient DMUs. The efficiencies of all DMUs are restricted to lie between 0 and 1 (Emrouznejad et al., 2011). One disadvantage of DEA is that the model cannot rank efficient DMUs. The results of models can be influenced by missing observations or leaving out important variables, not accurate data. Also, outliers can have an impact if they are the efficiency frontier. Zhou et al., (2018) reviewed the literature on DEA applications in sustainability. Research in sustainability often stresses on evaluation of the relationship between different pillars of sustainability. The three approaches to use the DEA model was mentioned: traditional DEA model with CCR and BCC approach, traditional DEA models with Malmquist production index to operate with dynamic time series data and the two-stage network DEA model where output on the first stage will play input on the second stage. The DEA does not give interpretation why certain HSRs economically, environmentally, or socially sustainable. The authors suggested that NDEA models should be used in combination with two-stage analysis.

With HSRs any poor performance can be related to poor technical efficiency or poor service effectiveness or a combination of both (Chiou et al., 2010). The HSRs cannot control external factors that influence the technical efficiency of railways such as GDP, density of population, level of using private cars and cost of fuel, but they can improve the service quality, punctuality, reduce travel time, improve the booking system, replace the rolling stock and infrastructure, etc. The projects that applied CCR and BCC DEA models is summarised in Table 2.1.

Table 2.1 Summary of projects that applied CCR and BCC DEA models (Source: Author's creation)

Author (s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Chambers & Cifter (2006)	Investigate the efficiency of scale on productivity of Turkish Banks	Turkey	CCR and BCC DEA	18	Branch numbers, personnel number per branch, share in total assets, share in total loans and share in total deposits	Total assets, net profit-losses, net interest income, net interest income/total operating income and non-interest income/total assets
Dhuci (2015)	Banking efficiency analysis	Albania	CCR and BCC DEA	14	Number of employees, number of bank branches, capital	Deposits
Graham (2008)	Analysis of productivity and efficiency in urban railways	Worldwide	CCR and BCC DEA	89	Number of employees, fleet capacity, route length	Passenger journeys per annum, passenger kilometres per annum and car kilometres per annum
Kumar & Gulati (2008)	Examination of technical, pure technical and scale efficiency in banks	India	CCR and BCC DEA	27	Fixed assets, number of employees, loanable funds	Net-interest income, non-interest income
Ramaj (2015)	To measure technical efficiency of hotels	Albania	CCR and BCC DEA	10	Number of employees, number of rooms, total cost	Average number of occupied rooms, total revenue
Watanabe & Tanaka (2007)	Efficiency analysis of Chinese industry	China	CCR and BCC DEA	219	Fixed assets, number of employees, coal consumption	Value-added of enterprises, Sulphur dioxide emissions
Marchesi & Wanke (2017)	Assessed efficiency of Brazilian rail	Brazil	CCR and BCC DEA	60	Labour, number of wagons	Tonne-km

2.3.2 The input and output-oriented DEA models

There are input-oriented and output-oriented DEA models. The input-oriented model measures relative inputs under constant output, and the output-oriented model measures relative output under constant inputs. The HSRs fit in the output-oriented DEA model, as input is fixed (infrastructure and rolling stock), but there is a need to look for ways to increase consumption outputs. Once an infrastructure and rolling stock investments have been made it is very difficult for HSRs to save the costs by altering their input variables.

However, some authors (Coelli et al.,1999) pointed out that the level of demand for public transport is connected to demographic and macro-economic factors and railways have limited control on the level of demand. For the transport industry, it is typical that services cannot be stored because this output production seat-km can differ greatly from output consumption-passenger-km. The process of production differs from consumption. Yu et al., (2008) in their paper related to Multi-activity Network Data Envelopment Analysis (MNDEA) defined four performance measures: passenger technical efficiency (PTE), freight technical efficiency (FTE), service effectiveness (SE) and technical effectiveness (TE).

Technical efficiency is defined as a ratio of outputs to inputs, service effectiveness as a ratio of consumption to output, and technical effectiveness as the ratio of consumption to inputs (Zhu, 2005). However, in this evaluation it did not take into consideration undesirables such as air pollutions, accidents, etc. Network DEA (NDEA) model allows to identify components inside a “black box” and evaluates organizational performance and its component performance. This is achieved by splitting the model into two or more stages, where an output of the first stage will be an input of the next stage (Doomernik, 2015).

Relationships between efficiency and effectiveness are described by Chiou et al., (2010). Technical efficiency measures success in the reduction of maximum inputs from a given set of outputs. Service effectiveness measures success in attracting maximum consumption from a given set of produced outcomes. Technical effectiveness measures DMU success in attracting maximum outcome (consumption) from minimum inputs. If output production (seats) is not sold they will be wasted (Yu, 2008). The surplus capacity at the low demand in off-peak hours cannot be stored for use at a high demand time. NDEA models should be used in combination with two-stage analysis.

Song et al., (2016) used the DEA model to measure the environmental efficiency of DMUs, taking into consideration undesirable outcomes. The efficiency of traditional DEA presumes an increase in outputs by the same time decreases in inputs. However, there can be situations when DMUs can decrease the amount of undesirable outputs by increasing the inputs. For example, introduction of new technologies that can reduce undesirable outcomes. Sameni et al., (2016) evaluated the efficiency of passenger railway stations using a two-stage DEA model. On the first stage, the authors evaluated technical efficiency of stations and on the second stage evaluated service effectiveness. The second stage model took output of the first stage-model as input, which is the number of trains stopping at a station.

Yu et al., (2008) presented a DMU model that combines production and consumption process in a single model and can be used for estimating technical efficiency, the service and technical effectiveness at the same time. The model includes the outcomes of transport services that cannot be stored and the technological differences within railway companies.

One of the major drawbacks of the DEA approach is the lack of discrimination among efficient DMUs (Angulo-Meza et al., 2002). To solve this problem, the Super Efficiency approach can be used. This method allows an efficiency score greater than 100 and provides a ranking of efficient DMUs in a similar way to a ranking of inefficient DMUs. This method was introduced for the first time by Andersen and Petersen (Andersen et al., 1993).

The DEA method has been used to investigate the efficiency of the world's railways and effectiveness in reducing costs by Yu et al., (2008). This analysis took aggregates of different disciplines of economy, mathematics, and management science. Yu et al., (2008) found that using different DEA models to evaluate a railway's performance does not alter the ranking of performance. Traditional DEA models presume that increasing outputs by the same time as decreasing inputs is a criterion of efficiency.

Karlaftis, (2004) found that a transport system efficiency and effectiveness are positively correlated and systems with a high efficiency score have a higher effectiveness score. This led to two measures of transport output: vehicle-km and passenger-km. The author estimated three separate sets of models with the same inputs but with different outputs. The first is an efficiency model with vehicle-km as output, the second is an effectiveness model with a total annual ridership as output and the third is a multi-output model using vehicle-km and annual ridership as outputs to evaluate a combined performance.

Amirteimoori et al., (2006) presented a DEA model that can analyse the situation when there are desirable and undesirable performance factors. An example of undesirable outputs can be air pollution and noise pollution. It is important to recognise desirable outputs and undesirable outputs and treat them differently. Sometimes, to improve the efficiency of DMUs some inputs must be increased and at the same time some outputs should be decreased.

Djordjevic, (2018) has used the improved non-radial DEA model which presumes to decrease the undesirable inputs and outputs to the greatest degree for the level of desirable inputs and outputs. The model calculates unified efficiency and reduces desirable inputs. The author used this model to evaluate railway efficiency regarding level crossings by considering desirable and undesirable outputs.

Doomernik, (2015) used DEA to analyse the performance of HSRs in a five-year period. The Total Factor Productivity (TFP) analysis allows to evaluate multiple inputs and outputs which resulting in a single index for efficiency. TFP index is used to compare productivity across countries. This index is heavily influenced by the output that was selected. The author used a two-stage Network DEA (NDEA) model that allows at the same time to evaluate technical efficiency, technical effectiveness, and service effectiveness. The DEA was used to evaluate the efficiency of passenger railway stations (Sameni et al., 2016) and to evaluate the efficiency of government investments in Japanese railways (Jitsuzumi et al., 2010). The achievement in attracting maximum ridership from the produced number of seats has been investigated by Yu, (2008). In the transport industry, output production in most cases will differ from output consumption. The projects that applied input-oriented CRS DEA model is summarised in Table 2.2

Table 2.2 Summary of projects that applied CRS DEA model (Source: Author's creation)

Author (s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Ahmad et al., (2017)	Analysis of efficiency in perspective of working capital management in manufacturing sector	Pakistan	CRS DEA	37	Total sales of firms, total profit after taxes, total assets	Cost of sales, total selling and administration expenses and cost
Pjevcevic et al., (2011)	Analysis of AGV fleet operations in a port container terminal	Serbia	CRS DEA	12	Number of AGVs, AGV active rate	Number of containers in queue, number of served containers
Sun et al., (2017)	Study evaluated environmental performance of the Chinese port enterprises	China	CRS DEA	17	Fixed assets, operational costs, labour	Desirable outputs- net profit, cargo throughput Undesirable output- NO emissions
Yu M-M (2008)	Investigation of un-storable feature of transportation services	World Wide	CRS DEA	40	Number of employees, the number of passenger cars, the number of freight cars, length of railway line	P-tr-km, P-km, f-tr-km, ton-km,

Some authors have highlighted that with European railways, it is not sure which model input-oriented or output-oriented must be used. Coelli et al., (1999) estimated both the input and output distance functions. Both models identified the same sets of DMUs as being efficient. Lan et al., (2005) stressed that when applying the economic approach to estimate efficiency and effectiveness, it needs to specify which function will be more appropriate, the production or cost. For HSRs, it will be suitable to use the production function. The cost function requires prices and total cost input data, which is difficult to collect. The projects that applied output oriented VRS DEA model is summarised in Table 2.3

Table 2.3 Summary of projects that applied VRS DEA model (Source: Author's creation)

Author (s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Coelli & Perelman (1999)	A comparison of parametric and non-parametric distance functions: with application to European railways	Europe	VRS DEA,	102	Labour, equipment, capital	Passenger services, freight services
Cesaroni, (2018)	Provide a method of implementation in DEA "cost minimizing industry structure"	Italy	VRS DEA	43	Number of employees, vehicles, composite of consumption of fuel, energy, materials and spare parts	Vehicle-km, size of transport network
Chen & Lam (2018)	Analyses of sustainable development of different port city systems	Worldwide	VRS DEA	20	Terminal area, number of equipment, land energy, number of employees,	GDP, CO_2 emissions
Jitsuzumi & Nakamura, (2010)	To analyse the reasons for the underperformance of Japanese railway services and optimum subsidy level method	Japan	VRS DEA	53	Related fixed assets, number of employees, operational expenditures (labour cost, tax and depreciation) Environmental/ uncontrollable factors- transport density	P-km, GDP per capita
Lai et al., (2015)	Evaluating the efficiency performance of airports	worldwide	VRS DEA	24	Length of runway, size of terminal area, number of runways, number of gates, number of employees	Aircraft movements, amount of freight, number of passengers, total revenues

2.3.3 Malmquist Index DEA model

Many researches applied Malmquist index to measure productivity change over time, and it is very useful as it requires only information of input and output quantities and does not need to have information on input and output prices which would be difficult to obtain. The Malmquist index shows if there has been an improvement over time in productivity and in technical efficiency and how the railways perform compared to the best performer. If the Malmquist index is greater than one, it means that it was an improvement in productivity, and if less than one, it means that productivity decreases. The Malmquist index is calculated under CRS.

Onour et al., (2011) applied the Malmquist index to measure productivity and efficiency changes of banks in North African countries. The downside of the analysis was that the research did not make any suggestions on how to improve performance of the banks. Sueyoshi et al., (2017) had the Malmquist index to measure sustainable enhancement in Chinese municipalities and provinces. They studied a dynamic change of the Malmquist index to examine the frontier shift in the selected period. The main contribution of the study was to analyse the relationship between magnitude of index change and the managerial disposability. The drawback of the study was that the assessment was not considered under all the configurations on the scale benefit.

Zhang et al., (2015) had the Malmquist index to measure dynamic change in total carbon emissions performance of the Chinese transport industry over the selected period. The Malmquist index had been decomposed into efficiency change and the technological change index. Zhou et al., (2007) applied the Malmquist index to measure the environmental performance of OECD countries over time. This approach presumes including desirable and undesirable outputs that are jointly produced. One of the limitations of the study is that the proposed model has weak discrimination power and if DMUs have the efficiency index one they cannot be directly compared and ranked. In this situation there can be two solutions. Firstly, it can compare efficient DMUs by the number of peers. Secondly, it can use the super efficiency approach. The summary of projects that applied Malmquist index DEA model is summarised in Table 2.4.

Table 2.4 Summary of projects that applied Malmquist index DEA model (Source: Author's creation)

Author (s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Pestana Barros & Peypoch, (2010)	Proposed framework for benchmarking bus companies	Portugal	DEA, Malmquist index	11	Liquid assets, labour, fuel costs, vehicle capacity	Sales, number of passengers
Doomernik, (2015)	Compared four Asian and Four European HSR systems to investigate the production efficiency and service effectiveness. The study also explores the differences between two regions, Europe and Asia, and strategies are proposed to improve the overall efficiency.	Asia & Europe	NDEA, Malmquist Productivity Index All efficiency and effectiveness scores and The Malmquist Productivity Index are calculated by using (Data Envelopment Analysis Program) software written by Tim Coelli (2001)	48	Railway network length, rolling stock capacity	Travel volume, ridership
Onour & Chebbi (2011)	Productivity and efficiency change of banks	North Africa	Malmquist index DEA	16	Salaries and wages, fixed assets and deposits	Loans, incomes
Sueyoshi & Goto (2015)	Environmental assessment of petroleum companies	Worldwide	Malmquist index DEA	17	Amount of oil reserve, amount of gas reserve, the total operational cost, labour	Desirable outputs-amount of oil and gas production Undesirable output-amount of CO2
Sueyoshi et al., (2017)	The study compares radial, non-radial and intermediate DEA approach	China	Malmquist index DEA	30	Labour, capital, energy	Desirable output-GDP Undesirable outputs-CO2, SO2, dust, wastewater
Zhang N. et al., (2015)	Investigation of carbon emission performance of the transportation industry	China	Malmquist index DEA	30	Capital stock, labour, energy	Gross product value-desirable output CO2-undesirable output
Zhou et al., (2007)	Evaluating the environmental performance of OECD countries	Worldwide	Malmquist index DEA	26	Labour, energy consumption	GDP-desirable output, CO2, Sox, NOx, CO-undesirable outputs

2.4 Conclusions

Evaluation of the sustainability of HSRs is a difficult task. HSRs have a difference in length of the railway networks, in cost of construction and have different technical approaches. To benchmark the performance of HSRs, two approaches have been used, which are Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis.

The DEA method measures the magnitude of technological changes and analyses economies of scale. More often the three models of DEA was mentioned: traditional DEA model with CCR and BCC approach, traditional DEA models with Malmquist production index to operate with dynamic time series data and the two-stage network DEA model where output on the first stage will play input on the second stage.

The results of all DEA approaches include the measured efficiency of selected DMUs, setting benchmarks for inefficient DMUs, and quantified parameters for increasing the efficiency of inefficient DMUs. This method integrates and transforms multiple inputs and outputs into a single efficiency index with a set of DMUs.

To evaluate the sustainability of the selected HSRs the Malmquist production index was selected as it offers more advantages, such as it gives the possibility to find if improvements can be seen over time, it does not require information on input and output prices which would be difficult to obtain and it is suitable for the small number of DMUs.

Chapter 3
Research Methodology

3.1 Introduction

The construction and operation of HSR has a huge impact on a country's budget, and in many cases only a small part of these investments will be recovered. The expenditure of public money can be found reasonable only if it improves the efficiency and quality of public transport, reduce the external costs, such as air and noise pollution, and reduces accidents and congestion. Most times, the reduction of external costs is a reason for spending public money on transport systems. It is important not only how much output it can produce from an input but what impact the project will make on the environment, accessibility, and neighbourhood.

It is difficult to benchmark sustainability of the HSRs as they differ in technical approaches, have different standards and they are built in different topographic areas. The cost of construction of HSRs also differ around the world. However, only the benchmarking of the performance of HSRs can help to find the best performer and calculate the targets on the performance improvement of the rest of HSRs. Analysing the best and the worst performers would enable finding the factors that influence the efficiency and productivity of HSRs.

3.2 Methodological approach of the research

The first part of this research is a literature study with the purpose to answer the questions regarding the different aspects important for a sustainable HSR and finding out the main related factors that affect the sustainability of HSR. Information gathered about the differences between HSR and conventional railways and differences between HSR and other mass-transportation modes. A broad literature review was carried out regarding the different HSR systems worldwide and applying NVivo software. The DEA method is employed to benchmark the performance of the selected HSRs whilst the IBM SPSS is used to find the factors that affect the efficiency and productivity of the selected HSRs. Figure 3.1 shows a flowchart of the methodology used to complete this research project.

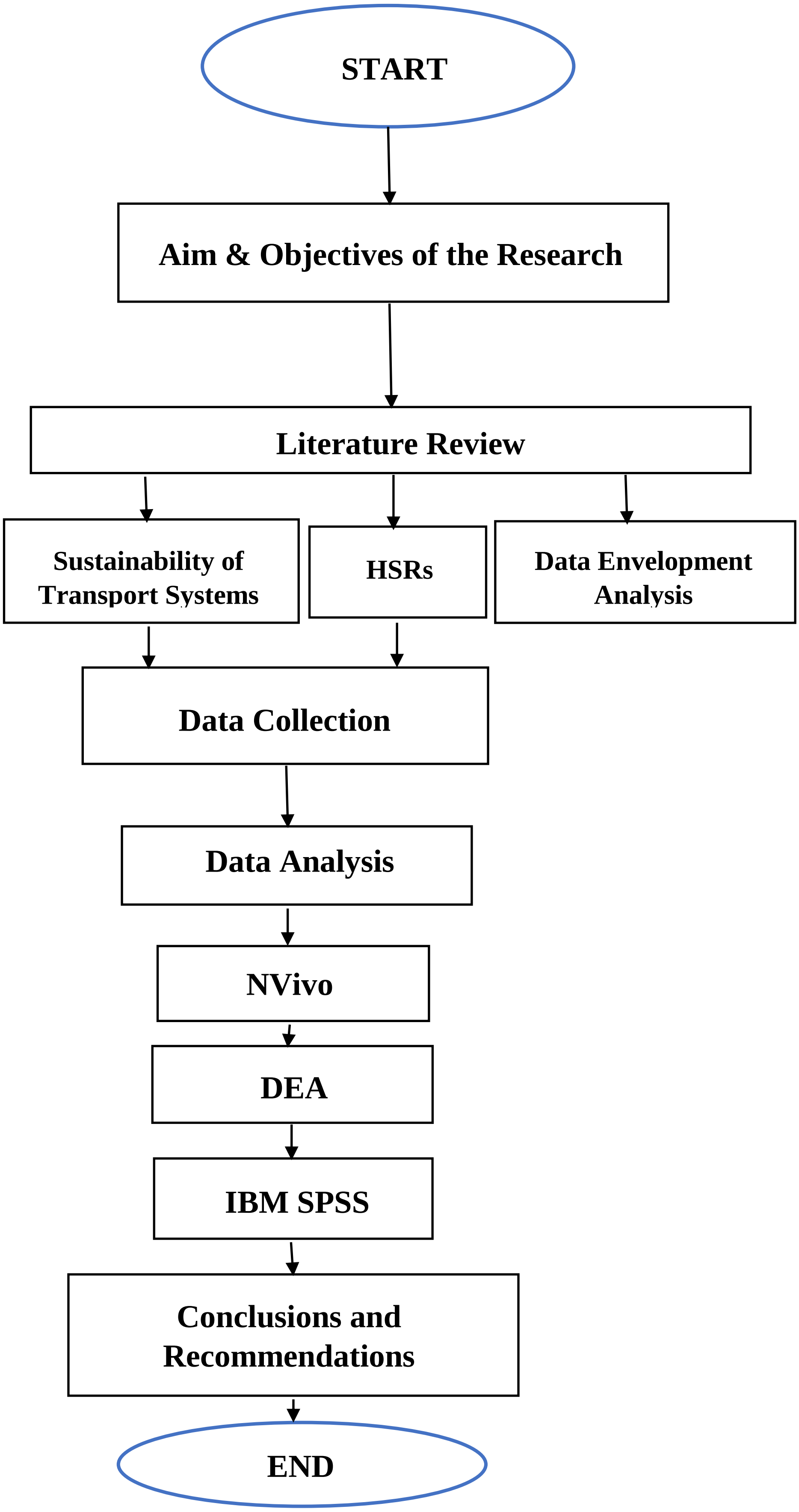

Figure 3.1 Flowchart of applied methodology (Source: Author's creation)

3.3 Selected software packages for data analysis

All information gathered from various sources, such as libraries, the Internet and meeting with relevant railway and transport professionals. Papers relevant to this topic were found using Google, Science Direct and Journal Article Search (EDS) engine at the London South Bank University. Keywords used in the search include high-speed rail, sustainability, social factors, economic benefits, safety, punctuality, etc.

3.3.1 NVivo software for qualitative data analysis

The package NVivo is used to prepare and analyse the collected data.

Using this software:

- Different types of data are analysed, such as Word documents, and PDFs.
- All relevant information is stored in one place, making it easy to navigate and search the data.
- NVivo helps to examine the potential relationship between topics.
- Can quickly discover the most frequently occurring words and display the results in a Word Cloud, where font sizes represent how frequently words occur.

Figure 3.1 shows the words that have been used for analysis of HSR most frequently.

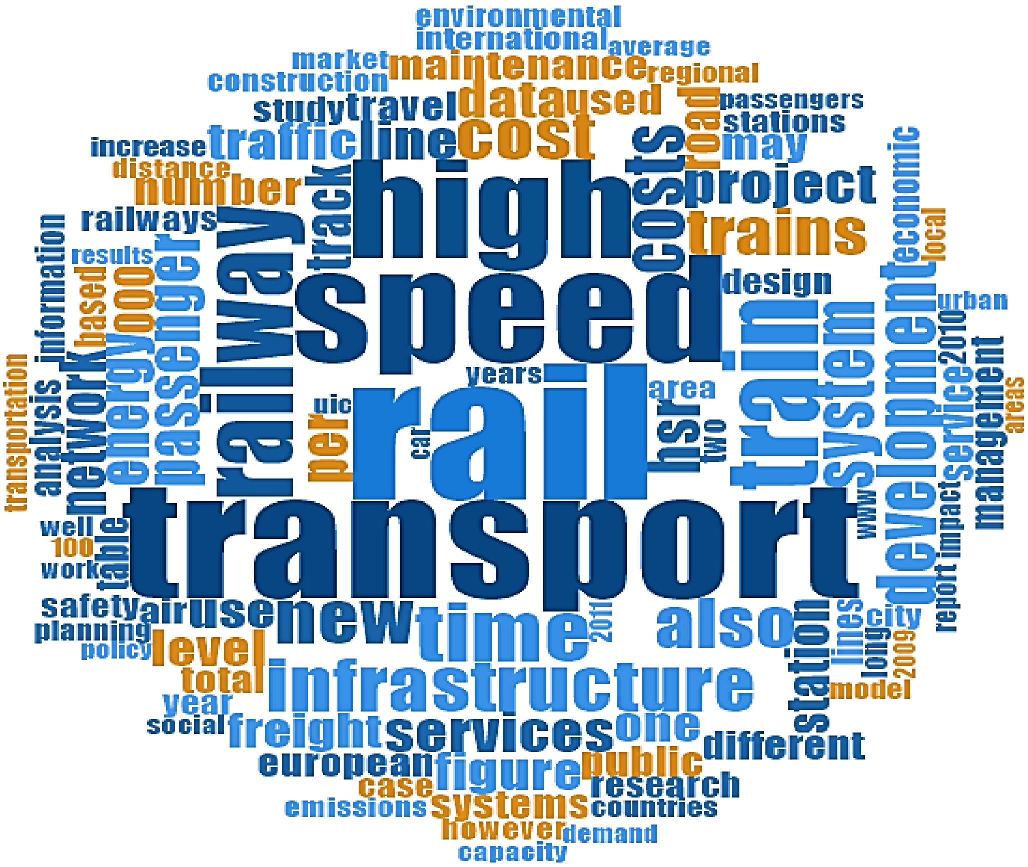

Figure 3.2 Word Cloud created by NVivo (Source: Author’s creation)

3.3.2 DEA method for quantitative data analysis

The study compares and evaluates the performance and efficiency of selected HSR systems in operation. It compares the efficiency of HSRs based on actual data and types of systems. For this study, the benchmarking methodology for the railway industry will be used. Benchmarking methodology presumes to compare the performance of selected HSRs with HSRs that are recognised as a leader in the industry to find the best practices and factors that influence it. This analysis is very suitable for the railway industry, as the industry is highly regulated and links between inputs and outputs cannot be clear (Doomernik, 2015). This research has compared the number of passengers and passenger-km with the input, which is the length of the HSRs network. Benchmarking the selected HSRs can give recommendations to the best practices in sustainability. To benchmark the performance of HSRs mostly two approaches have been used, which are Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis. Because of the limitation of available data to benchmark performance of HSRs the DEA approach was selected.

To analyse the performance of HSRs, first a need to identify outputs that a railway produces and inputs that was used to produce these outputs. Jain et al. (2009) took for the inputs, labour-number of employees, capital-number of train sets and the total network length of lines. These inputs will produce outputs, passenger trips, and train-km. In the present research, only the main assets the HSR infrastructure and rolling stock have been taken into consideration. In the DEA analysis, the length of HSRs have been used as an input.

- The DEA is a method that measures the efficiency of similar Decision-Making Units (DMUs).
- This method is more appropriate for evaluating efficiency of HSRs as the sample size is small and input values do not vary substantially over time.
- The DEA defines the relationship between the outputs that the HSRs can produce and the inputs and aims to estimate the relative efficiencies of HSRs.
- The number of DMUs must be at least twice the number of inputs and outputs combined.

The DEA analyses the performance of selected HSRs, identifies high and low performers, and finds the best practices within a selected group. It then passes to an analysis of the reasons for variances in performance, which will lead to an investigation of the differences in process methods or uses of different technologies. There are many factors that can affect the performance of HSRs such as the change of climate, changes in density of population, economic and political crises, etc. For this research, the Circular Malmquist Index approach has been selected. The DEA CMI permits breaking up the overall efficiency from the CRS results in technical change and efficiency change. This approach analyses productivity score changes of selected HSRs observed over the period 2010-2017 and allows a comparison between HSRs.

Figure 3.3 shows a flowchart of the evaluating performance of HSRs based on the efficiency frontier approach. If TE score is equal 100% it records HSR as efficient, if TE is not 100% HSR needs to increase the number of passengers or passenger/km to be efficient. However, HSR can be recorded as fully efficient only if a slack is equal zero, if it is not equal zero it needs to increase the number of passenger or passenger/km for HSR to be fully efficient.

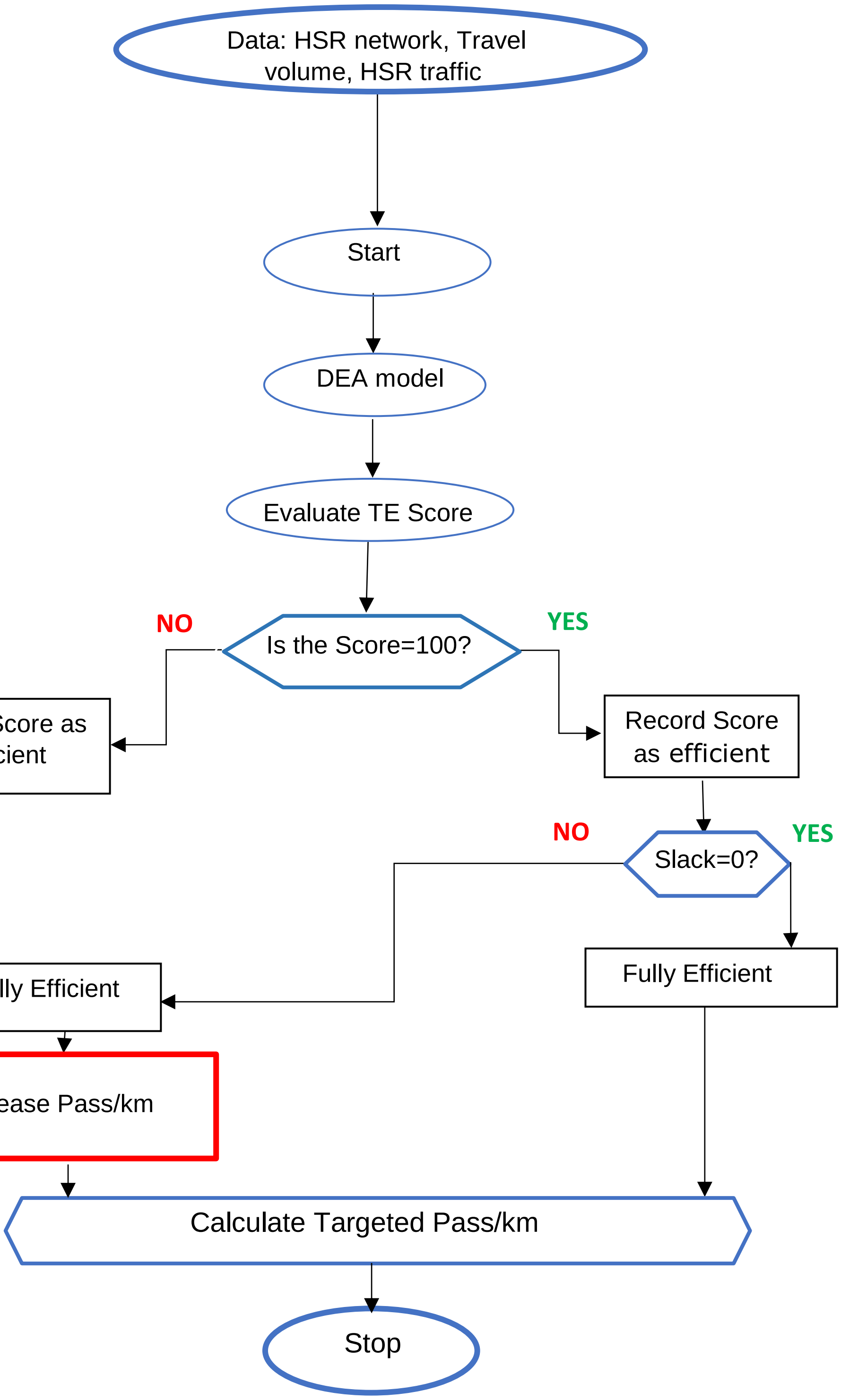

Figure 3.3 Flowchart of the evaluating performance of HSR based on the efficiency frontier approach (Source: Author's creation)

3.3.3 IBM SPSS statistics package

In the third stage, the research concentrated on finding the factors that influence the performance of HSRs. To help find which of the factors has the largest influence and which has less, the Regression Analysis has been employed. To statistically analyse the results of the DEA approach and selected variables, the IBM-SPSS Statistics software has been applied to:

- Study statistics of selected variables
- Produce scatterplot OTE and selected variables
- Calculate Pearson correlation test

3.4 Conclusions

This study proposes an integrated approach to evaluate the efficiency of the performance of HSRs and the factors that affect their performance.

- NVivo is used to prepare and analyse the collected data.
- DEA is used to compare and evaluate the performance and efficiency of the selected HSR systems.
- IBM-SPSS is used to identify the factors that influence the performance of the HSRs and to statistically analyse the results of the DEA and selected variables.

The expected outcome of this research will contribute to identifying areas of improvement and contributing to the development and advances of more sustainable HSR systems.

The contribution of the present study comes mainly from the following areas:

- Decomposition of overall technical efficiency (OTE) into pure technical efficiency (PTE) and scale efficiency (SE).
- Evaluating the relationship OTE and productivity with selected variables by applying IBM-SPSS Statistics.
- Distinguishes the factors that contribute to the sustainable performance of HSRs

Chapter 4

HSR Systems in Selected Countries

4.1 Introduction

According to the UIC on 1st October 2020, there are 20 countries worldwide that have HSR in operation; thirteen countries in Europe (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Poland, Czech Republic, Spain, Switzerland, the Netherlands and the UK), three country in Asia (China, Taiwan-China, Japan, South Korea) and four other countries (Saudi Arabia, Morocco, Turkey and the USA).

The first HSR system was introduced in Japan in 1964, later followed by Italy in 1977, France, Spain, and Germany and by 2025 there will be 24 countries that have HSR. The operational characteristics of high-speed lines are speed and length of lines. There is a need to separate maximum track speed, maximum operational speed, and commercial speed. Maximum track speed depends on the technical parameter of infrastructure, maximum operational speed depends on the technical parameter of rolling stock and commercial speed is the ratio between length of track and total travel time (Ems.expertgrupp.se., 2019).

The length of high-speed lines varies from 22km, which is La Sagra-Toledo, in Italy to 2,298km which is Beijing-Guangzhou in China, the longest line in the world. China has six from ten of the longest high-speed lines in the world. In Europe at that moment, the longest high-speed line is Madrid-Barcelona-French Border, 804km and belongs to Spain (Railway Technology, 2019a). Demand for travel on HSR depends on many factors and most important of them is the density of population and personal income. Demand for travel varies from country to country. In Japan, there are on average 353 million journeys on HSR every year, in Europe this figure is much less (World Economic Forum, 2019).

4.2 Case studies

For this study, ten HSRs worldwide are studied, six in Europe and four in Asia. Figure 4.1 shows the map of Eurasia with selected operators of HSRs.

Figure 4.1 Map of Eurasia with selected operators of HSRs (Created by Author)

Between selected HSRs, there are some technical and organizational differences, such as a difference in operating voltages (Spain), different gauges (Spain, Japan), signalling systems (France, Germany), and languages (Eurostar). The most challenging of them is the Eurostar which crosses three different railway networks. It has three different power collection systems and signalling systems for Belgium, France, and the UK. The future of the European rail network is in standardisation and integration of existing and new build systems. Table 4.1 shows the data pivot table related to selected HSRs. The data refers to 2017. According to the UIC "World HSR Rolling Stock" Germany has 6 train sets powered by diesel. They are not considered in this research, as it is investigating only the electrified HSRS.

Table 4.1 Selected HSRs in 2017 (Created by Author), Data taken from various sources

Selected Countries with HSR	Average operational train speed (kph)	Length of HS lines with speed 250kph and over (km)	HS traffic passenger-km (millions)	Number of passengers (thousand passengers)
KR	154	887	14869	59669
ES	202	2852	15540	40259
DE	168	1658	28502	86732
TR	149	724	2218	7160
TW	152	354	11103	60570
NL	130	120	413	4098
FR	243	2814	58280	108720
CH	282	26869	577635	1517800
IT	191	896	12997	41276
JP	203	3041	101325	377743

Table 4.1 shows the huge differences between selected HSRs in size of the railway network, average operational train speed, total number of HS train sets, average traction power of HS train sets, the number of passengers and passenger-km. Apart from technical and organizational differences in selected HSRs there are also topographic differences, differences in surface area of a country, in size of population, in purchasing power, and in GDP per capita.

4.2.1 HSR in Japan

The core of the success of the Shinkansen (a network of high-speed lines in Japan) lies in the decision to build dedicated lines for high-speed trains. Before the decision had been taken a few other options were discussed. First, the size of gauge for the track that would be used: Japanese-gauge (1067mm) or standard-gauge (1435mm), second, build the HSR alongside the existing line or develop a new corridor. Behind the reason to build the line in a new corridor was that the existing line had too many sharp curves for the high-speed trains (Japanese Railway Technology Today, 2001).

Another reason was that the new track layout would affect many people, as the area along the railway line is densely populated. At the end, it was decided to provide a new double track high-speed standard-gauge line for speeds up to 250km/h. It was innovative to operate commercial services at this speed. Because of geological and geographical conditions in Japan, HSR requires many long tunnels and bridges. The disadvantage of this decision was the very expensive civil engineering work, approximately 13% (86km) of the line is in tunnels, and 33% (174km) on bridges and viaducts (Japanese Railway Technology Today, 2001). HSR infrastructure in Japan must be resistant to earthquakes, floods, and deep snow.

There is no plan to increase the speed on the Tokaido-Shinkansen line. The line originally had been designed for lower speeds that can be achieved by the new generations of high-speed train. Having fewer trains with very high speeds, it would be difficult to fit all the existing slower trains in a timetable. Also, the tracks lay in an area with a high-density population and with very strict environmental constraints. With the increase in speed it increased the level of noise and vibration. One of the solutions to be found was to make trains lighter and smaller. Another solution is to reduce the noise level from pantographs and bogies. Japan was the first country to set environmentally acceptable noise levels for high-speed trains.

Shinkansen is the great economic success of Japan, and today the Shinkansen has an operational revenue of around $19 billion a year (ISO, 2019). This success has many reasons, and one of them is that the railway company owns the entire infrastructure, stations, the rolling stock, the track, and land around the railways. There is less bureaucracy, less management and decisions are taken more quickly. With the future decline in Japan’s population from the current 127 million possible to 96 million by 2050 (Worldpopulationreview.com., 2019) there will be a slowdown in new developments of HSR, as there will not be enough demand for high-speed trains.

4.2.2 HSR in France

High-speed trains were introduced in France over three decades ago in 1981. However, after 33 years of operating high-speed trains in France, almost 40 percent of these trains travel on conventional track (International Railway Journal, 2019b). Around 60 percent of TGV trains are travelling on new lines designated only for TGV and all other traffic was prohibited. The new lines have higher gradients unsuitable for freight traffic. In France, the new HSR's were designed to avoid tunnelling, and this gives the benefit of the possibility to implement the double deck trains. The TGV Duplex was introduced in 1996, this train can travel at speeds up to 300 kph (Railway Technology, 2019d). The big achievement of the HSR system in France is that the TGV system is compatible with existing conventional railways.

There are two different ways to power high-speed trains: it can be as in Japan, with distributed traction, or as in France, with TGV, centralized traction. With increasing awareness about the damaging effect caused by transport on the environment and looking for ways to increase efficiency of transport it looks more economically appropriate to use distributed traction to power high-speed trains.

There are other ways to increase the capacity of trains and one of them can be double-deckers (France, Germany, and Japan) or the widening of carriages (Sweden, Japan). Increasing the capacity of trains gives the possibility to reduce operational costs, and this can reduce the railways' fares. To increase capacity of railway lines it is needed to electrify the line, implement more advanced signalling systems, increase speed of trains, and have dedicated lines for high-speed trains only.

From 2008 the profitability of TGV steadily declined, and it was pronounced that there was a need to reduce several stations served by TGV to make HSR network profitable. HSR services carry only 7% of passengers, but accounts for 61% of the total French rail network traffic. In France, high-speed trains serve 230 stations (International Railway Journal, 2019b).

There has been a lot of pressure from local governments to open more stations, and in this case the HSR in France lost the aim of high-speed trains, which is to connect only high-density populated centres with frequent services and only with a few stops. Since the economic crisis in 2007, the number of passengers using the high-speed trains continues to decline, also operation margins fell from 29% in 2008 to 12% in 2013, and new lines are now not as profitable as had been predicted. For example, TGV Nord has only 5% profitability, but was forecasting 20% (International Railway Journal, 2019b).

The high-speed trains are the most efficient mode of transport. This is one reasons that society continues to fund HSR services. HSR gives time saving, energy saving, improves accessibility, increases economic activity, and generates employment. However, with a low-density population in France and only a few larges populated urban areas, it looks unlikely that in the current condition the HSR will be profitable.

4.2.3 HSR in Spain

Construction of the HSR in Spain began in 1989 in the corridor between Madrid and Seville, and high-speed trains (AVE) started to run in 1992. Spain's HSR network is one of the widest in the world. In 2018, the length of the HSR network was 2852km and 904km were under construction. Spain is planning to build another 1061km, with an average cost of €14m per kilometre. Only China and Japan have more kilometres of HSR lines (Uic.org., 2019c).

The success of HSR around Europe is in part because of the interoperability with existing lines (France and Germany), but in Spain this is not the case. Conventional lines in Spain have a gauge of 1668mm. The difficulty of the Spanish railway network is that it has two different sizes of rail line gauges: standard gauge (1435mm) and Iberian gauge (1668mm). Some new lines are being constructed to allow trains with standard and Iberian gauge wheels to run on the same track.

There have been dramatic changes in accessibility of high-speed trains in Spain, and by 2020, 90% of the population will have an HSR station within a 30miles radius. In the last ten years, the Spanish government has put more financial resources into developing HSR than in highways (News.bbc.co.uk., 2019). The Spanish HSR have significantly increased the level of accessibility to access trains and stations by installing elevators, moving stairways, and offered help for vulnerable passengers when entering the train.

The new generation of Talgo trains is Talgo Avril. This train is designed for speeds up to 380km/h, with a low floor to improve the accessibility for vulnerable passengers. The train will consume less energy because of its lightweight construction, will produce less noise and vibration, and generate less carbon dioxide emissions.

The development of railway infrastructure in Spain, as in Germany, is the responsibility of the State. Spain subsidises HSR heavily, and the cost is around $3billion per year (Bodman, 2019). HSR in Spain on many routes is not profitable because of the low occupancy of trains. There are a few reasons for low occupancy: high unemployment, high ticket prices, many towns with HSR stations are small and can only generate a few passengers. Because of the high cost of developing the HSR system, it looks that the development of the HSR systems in Europe and around the world will be in the majority financed by public funding.

4.2.4 HSR in Germany

The development of HSR in Germany relieved the increasing demand for air and auto travel. Germany has twice the density of the population of France and taking into consideration that the territory of Germany is smaller than that of France, this can be a good foundation for success of the HSR system.

The HSR now connects all the largest cities of Germany, and it is in the centre of the country's transport system. From the beginning DB (German Federal Railways) allowed all categories of trains, including high-speed trains and freight trains to use the conventional lines and HSR lines also, but only some trains must run at a lower speed. This decision to allow freight trains to use the HSR was due to the amount of income that freight transportation brought into Germany. This decision differed from Japan and France, where HSR lines are dedicated only for passenger traffic. The mix of traffic brings some disadvantages, for example, if trains with different speeds use the same line, it will decrease the line capacity and can increase the safety problems.

Many railways tracks have been upgraded in Germany, but with the mix of traffic, German HSR lines cannot compare with the French network. To travel fast, there is a need to have not only advanced rolling stock but modern infrastructure too. Travelling time in France will be half of that in Germany for the same length of a journey on railways.

Another reason that affects travelling time on DB is that there are too many stops for high-speed trains in rural areas with not enough demand for passengers travelling on trains. It must be a combination of trains that have many stops and direct trains similar as on Tokyo-Osaka route. Shinkansen has a good mix of direct trains with only a couple stops or none, and trains that serve numerous stations.

With increasing awareness about climate change and the finite of natural resources, it is getting more important to look on what type of energy was supplied for HSR. Most of the energy used by DB is generated from fossil fuels. As shown in Table 4.2.

Table 4.2 Breakdown by origin of electricity used by the railways in 2005 (Source: Ec.europa.eu., 2019c)

Member State	**Solid Fuels**	**Oil**	**Gas**	**Nuclear**	**Renewable**	**Total**
Belgium	11.8%	1.9%	25.3%	58.1%	2.9%	100%
Germany	54.0%	0.1%	8.3%	26.7%	10.9%	100%
Spain	38.0%	3.8%	18.3%	21.5%	18.4%	100%
France	4.5%	1.8	3.2%	85.8%	4.7%	100%
Italy	33.8%	10.0%	41.5%	0.0%	14.7%	100%
UK	37.0%	1.0%	37.0%	20.0%	5.0%	100%

In recent years, in Germany, HSR systems have lost a considerable number of passengers to long distance coaches. From October 2014, DB started to withdraw some trains as competition between long-distance trains and coaches increased (Europe, 2019). It looks that DB needs to review the price policy to remain competitive.

To construct, operate and maintain the HSR system is very expensive and after implementing the HSR systems some governments are left with not enough money to upgrade existing railway systems (France). All HSR lines in Germany need to be subsidised by the government. To be successful, HSR needs to be socially, economically, and environmentally sustainable. With a high population and several important administrative and business centres, Germany has a good potential to have a profitable HSR system.

4.2.5 HSR in Italy

Italy was the second country after Japan that introduced high-speed trains and the first train went into operation in 1977, but the line was only completed in 1992. Italy was the only country in the world that opened the HSR network for competition. From 2012, NTV (Nuovo Transporto Viaggiaton) a private HSR company began to operate. Because of the lack of data in this research, only data related to one company, Trenitalia have been taken into consideration.

The Italian transport system favoured roads, but this raised concerns about environmental impacts from transportation. In 2003-2004, only 5.9% of passengers and 16.5% of freight was transported by the railways (Global Railway Review,2019). With expanding the HSR network and upgrading conventional lines, HSR will be more attractive to customers.

Most of the lines have advanced signalling equipment (ERTMS). There was some back down in the integrated Italian HSR network in European system, as Italy has some HSR lines using 3kV DC electrification instead of the standard European system of 25kV AC. Building the new HSR lines and upgrading the conventional lines has successfully reduced the number of domestic flights and car journeys in Italy. With the reduction of flights and car travel, it cut the amount of produced GHG emissions by the transport sector. One of the significant features of the Italian HSR network is the wide introduction of ERTMS that it integrated in interconnection with the European railway network. It opened the possibility to drive the same rolling stock with the same team around Europe with no need to change on the border and carry on at speeds up to 300kph. With building the HSR lines in Italy, they delegated conventional railways to freight transport and to serve the regional passengers.

4.2.6 HSR in China

China has the largest HSR system in the world, approximately 60% of the length of the world's HSR network. The Chinese government has aimed to connect all cities by HSR that have a population of 500,000 or more. At the end of 2020, the total length of new build HSR lines and upgraded will reach 50,000 kilometres (UIC, CER, 2015). It will connect south and north of China and west and east. The next step will be to connect China with Taiwan by an underwater tunnel.

The development of the future HSR system in China involves a huge amount of money, but with the slowing down of the economy in China it looks a very ambitious plan. Although, that the cost to build 1km of HSR in China is cheaper than in Europe. As estimated by the World Bank, it is between $17-21 million, in Europe it is between $25-39 million (World Bank, 2019). China has some very advanced ideas, and one of them is to connect major cities in the world by HSR, such as London, Moscow, and Paris with Beijing. “One Belt-One Road”, is a concept that will connect central Asia with Europe and further (Cheung, 2019). This project involved over 60 countries with more than half the global population.

Passenger traffic on HSR is growing rapidly from 128 million in 2008 to 672 million in 2013 and by 2014 over 2.9 billion passengers used HSR (Documents.worldbank.org., 2019). HSR is still not profitable. One reason can be that ticket prices are too expensive for passengers. The average population do not earn enough money to travel by HSR, GDP per capita in 2014 was $7000 (Documents.worldbank.org., 2019). Also, many HSR stations in areas where there would be low passenger occupancy. China has a very controversial way how to increase the demand for HSR, they just cut down the number of conventional trains and put passengers in a position when they do not have any other choice apart from HSR.

China has some unproportioned population density with more people living in the east part of China than in the west. Development of new HSR will help to satisfy increasing demand in travel to the east of China.

Development of a big infrastructure project, such as HSR, plays a very important part in creating new jobs and boosting the economy in areas where the railways go through. The HSR systems in China have weak competition from road transport, bus services do not expand around the country, also not so many people own cars. The real competition is from airlines and conventional railway lines. Cutting the number of conventional trains, it makes the position of HSR stronger. However, this does not help to reduce the deficit of HSR which makes HSR unsustainable.

4.2.7 HSR in Turkey

The first HSR which is 232km long was opened in 2009 from Ankara to Eskisehir with a maximum operational speed of 250kph and targeted to transport 9 million passengers annually (UIC, CER, 2015). The railways have approximately 1% of a share in passenger transportation (Uysal, 2019a). Turkey has a target for the future to increase the share of railways to 10% in passenger transportation and to 15% in freight transportation (Railway PRO Communication Platform, 2019a). HSR will connect sixteen of the largest cities and the government is planning to connect 55% of the population within an HSR network by 2023 (Railway PRO Communication Platform, 2019b).

Turkey's long-term vision for HSR is to carry passengers and freight from hubs around the country and beyond. Turkey wants to integrate into the EU and be a part of the European Single Market and part of the European Transport Network. Turkey has a very favourable location, as a bridge between the Middle East and Europe, and this location gives many advantages. One of them can be The Silk Road Project, which will connect China and Europe by passing through Turkey, which will increase freight and passenger traffic on HSR.

The Turkish government has ambitious plans by 2023 to interconnect all major metropolitan and industrial areas by the HSR network, and passenger numbers can increase to 945 million per year. The development of HSR is funded mostly by the government and by credits from foreign banks (Transport-exhibitions.com., 2019). Turkey has the 5th largest HSR network in Europe and the 9th largest in the world. The one of Turkey's targets is to manufacture all HSR stock in house and convert existing RS to be compatible with HSR.

4.2.8 HSR in Taiwan

The HSR in Taiwan comprises one double track line 354km long. The line runs along Taiwan's western corridor from the capital of Taiwan (Taipei) to the main industrial city of Kaohsiung on the south of the island. These are the two largest cities in Taiwan. The first 345km of HSR in Taiwan went into operation on 5th January 2007 with a maximum operational speed of 300kph (News, 2019).

To avoid crossing roads on the same level, 90.7% of the line was built in tunnels and on viaducts. The total cost of HSR was estimated to be $15 billion (Bradsher, 2019). This line links towns and cities with 94% of the total population in Taiwan.

The development of this line reduced the number of car journeys and the number of flights. As a result, it reduced the dependency of Taiwan on the export of petroleum and reduced CO_2 emissions from the transport sector.

The development of HSR decreased the number of flights and car trips. The number of domestic air passengers in 1997 was 18 million, but with the HSR coming into operation, it dropped to 6 million in 2007 (Focustaiwan.tw, 2019a). In 2017, the number of passengers using HSR increased to 60.57 million with 198 daily services. The total number of trains reached 51751 with a 65.16% occupancy rate. The initial ticket for a 345km journey cost $44. It is two-thirds of the airline ticket price (Bradsher, 2019). THSRC has an excellent punctuality rate of 99.72% (Thsrc.com.tw, 2019).

The HSR in Taiwan is based on the technology of the Shinkansen. This is a new line, and as often to reduce the cost of the project, the stations are located outside of cities. Passengers can reach a station by a free shuttle bus from the centres of towns. In 2017, it provided 393,819 free shuttle journeys (Thsrc.com.tw, 2019). Also, each station has parking space, car rental service, taxi, metro, and bus services.

In 2015, Taiwan High-Speed Rail Corp (THSRC) a private company that built and operated HSR in Taiwan, was close to bankruptcy. This was caused by a wrong projection of ridership and high depreciation costs of trains. Also, the high price of tickets deterred people from using the HSR. The government stepped forward and saved the THSRC from bankruptcy (U.S., 2019).

4.2.9 HSR in South Korea

The HSR network in South Korea comprises two corridors, one from Seoul to Busan, an area where over 70% of the population lives and another one from Seoul to Gwangju. The estimated cost of 411km HSR from Seoul to Busan was $US17 billion. It was an expensive project, as 190km is in tunnels and 120km on bridges and viaducts. The HSR network will be expanded for commuters to travel to most parts of the country in 1hour 30 minutes (Systraasia, 2019).

It was a huge joint South Korea-France project that involved sending 1000 South Korean engineers to France for training and to adopt French experience in developing and operating the HSR system.

The Seoul-Busan corridor represented 65% of passengers and 70% of freight flows. Because of this, the development of HSR in South Korea improved environmental sustainability by reducing around 33000 cars and 8000 buses per day, reduced congestion on the Gyeongbu Expressway, reduced travel time. Also, this supported demographics and economic decentralization and improved the quality of travel (Railway Gazette, 2019). After three years of exploitation, Korea Train Express (KTX) in the corridor Seoul-Busan captured over 60% share of all travellers. The number of air travellers dropped from 3.8 million in 2004 to 2.4 million in 2008 (Korea JoongAng Daily, 2019b).

The HS trains which were developed in Korea caused many safety concerns as they had many technical problems. In 2011, one of the HS trains was stopped for an hour inside a tunnel. In 2018, a KTX bullet train derailed, and 14 passengers were injured (koreatimes, 2019). The Korean's Government has ambitious plans to extend HSR from Mokpo to the largest island in Korea, Jeju. To implement this plan, Korea must build a 73km underwater tunnel, the largest in the world.

In the later years, there can be observed an increase in competition from road transport as the Government investments in railways is insufficient. From 1971 to 2004, the length of railway lines in Korea decreased, which increased the number of cars on the road. Also, increased safety concerns about using KTX. All of this negatively influenced HSR ridership, which dropped from 16.3 million in 2016 to 14.9 million in 2017 (Uic.org, 2019).

4.3 Comparison of high-speed rolling stock in the selected countries

The HSR is defined as a system that operates at 250kmph or more and it requires specially designed train sets. HSRS can be divided it two groups. The first group it is long life HSRS with renovation and the second group is HSRS with short life without renovation. In Japan, HSRS was designed for a 15-20-year life cycle, but in Europe it is around 30 years (Uic.org., 2019b), and because of this HSRS in Japan do not need to go through a major renovation within their life cycle.

Current design philosophy for rolling stock in Europe is to allow for thirty to forty years of service-life. Often the rolling stock has been used and after forty years to cover as many kilometres as possible for the initial financial spending involved. There is a need to look at the balance between economic benefit and energy consumption. For the future may be more appropriately cheaper, lightweight, shorter life but low maintenance trains. Shorter lifespan rolling stock will allow faster implementation of new technologies, have more modern trains, and it will revitalise railway manufacturing industry. These types of trains have been successfully developed in Japan. RS of selected HSRs has different technical characteristics and different capacity. Figure 4.2 shows comparisons of cross sections of Japanese N700-I and European high-speed train.

In Europe, for new build HSR used loading gauge C, in Japan it is 250mm wider, that allows to have a five seats rows. Wider loading gauge allows to increase capacity of seats for HSRS.

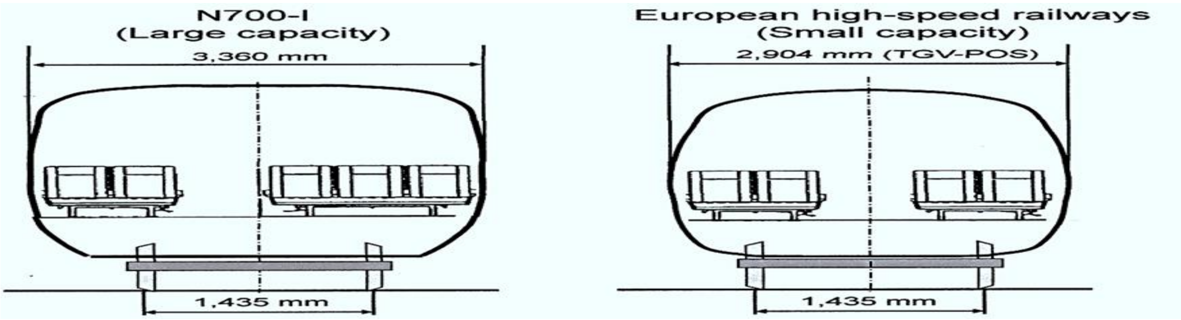

Figure 4.2 Comparisons of cross sections of Japanese N700-I and European high-speed train (Source: Amended from www. jterc.or.jp)

The modern HSRS more often has distributed power system as this type of RS has better traction performance. All HSR trains in Japan have distributed power system. N700-2000 is one of the latest Shinkansen trains that can be formed from 16 cars (14 motor coaches and 2 trailer coaches) with a capacity of 1323 seats (Uic.org., 2018a). The maximum length of trains in Japan is the same as in Europe, which is 400 metres. With increasing the length of noses of HSRS decreases the capacity of train. To optimise the capacity of EMUs the nose of trains should be as short as possible (Source: Uic.org., 2018a).

Some HSRs operate double decker trains, which can double capacity with same number of staff. Example of this can be France. Downside of this type of train is that it has reduced accessibility for passengers with restricted mobility. This trains have higher axle load and weaken resistance to cross winds. To reduce the time of embarkation and disembarkation of passengers it was beneficial to have HSRS floor height in level with platforms. This can reduce the total operational time of trains.

One of the important technical characteristics of HSRS is an axle load. Need to look to minimise the axle load to reduce the energy consumption, reduce the infrastructure maintenance, and increase speed. One of the most important developments in the construction of TGV-PSE, in France, was the introduction of articulated suspension between passenger vehicles. Using this innovation, it can reduce the weight of the train as the bogie is one of the heaviest components, reduce the aerodynamic drag, decrease the level of noise from the train, reduce the bogie maintenance, and improve passenger comfort. Also, with reduce the number of bogies, reduces the derailment chance. Figure 4.3 shows non-articulated and articulated bogies of HSR trains.

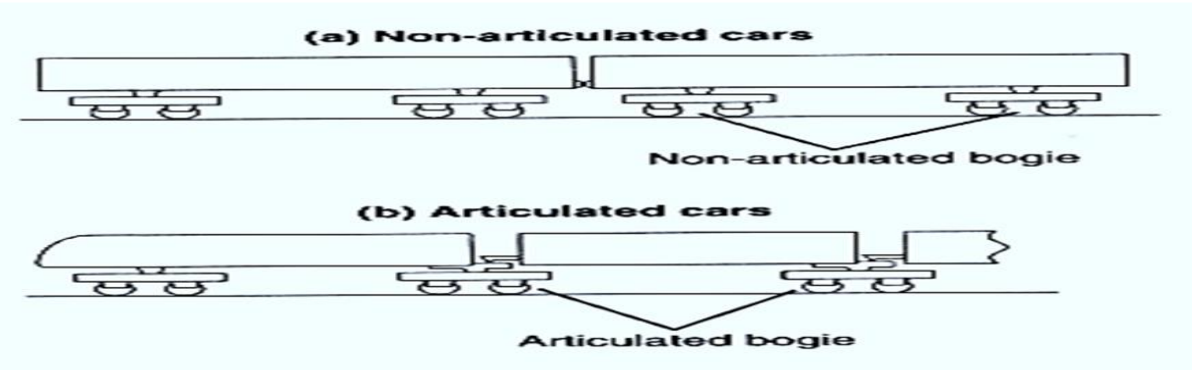

Figure 4.3 Non-articulated and articulated bogies (Source: Japanese Railway Technology Today, 2001)

A traditional coach has two bogies, and each bogie has two axles; on TGV-PSE coaches each bogie supports two coaches. The car length of articulated HSRS is 13-19m, non-articulated HSRS the car length is approximately 25m (Uic.org., 2018a).

Advantages of articulated trains are a more comfortable ride, passengers on the train are less affected by running noise, but the downside of articulated trains are increased axle load and maintenance of these bogies are more difficult. Also, lower capacity of the same train length. To extend track formation life and increase the speed of trains, the weight on 1 axle was restricted to 17 tons (Uic.org., 2018). Minimizing the axle load will reduce infrastructure and other structural maintenance, reduce the construction costs, and reduce the noise level. Train with distributed power has less axle load and higher capacity than trains with concentrated power.

The tilting technology prevents passengers from having some discomfort from the lateral acceleration, also much cheaper than having to build new tracks. This technology allows the train to have higher speeds in curves, which can reduce the journey time. Figure 4.4 shows the tilting bogie technology in Japan, called passive tilt

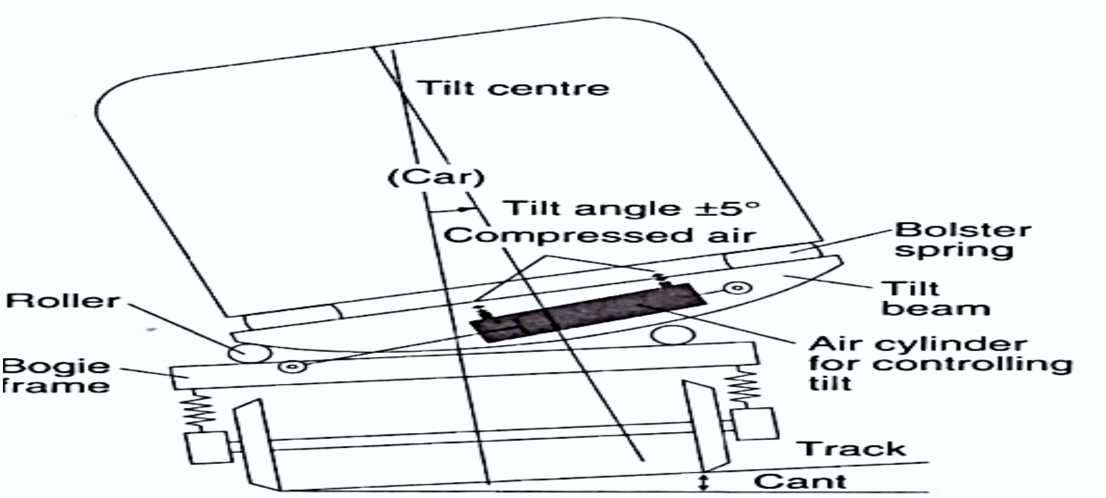

Figure 4.4 Roller type tilt system (Source: Japanese Railway Technology Today, 2001)

When the train runs on a curve, the tilting system tilts the body of carriage up to 5º gradient (Japanese Railway Technology Today, 2001). Also, another tilting system has been developed, the controlled tilt system, called active tilt Figure 4.5

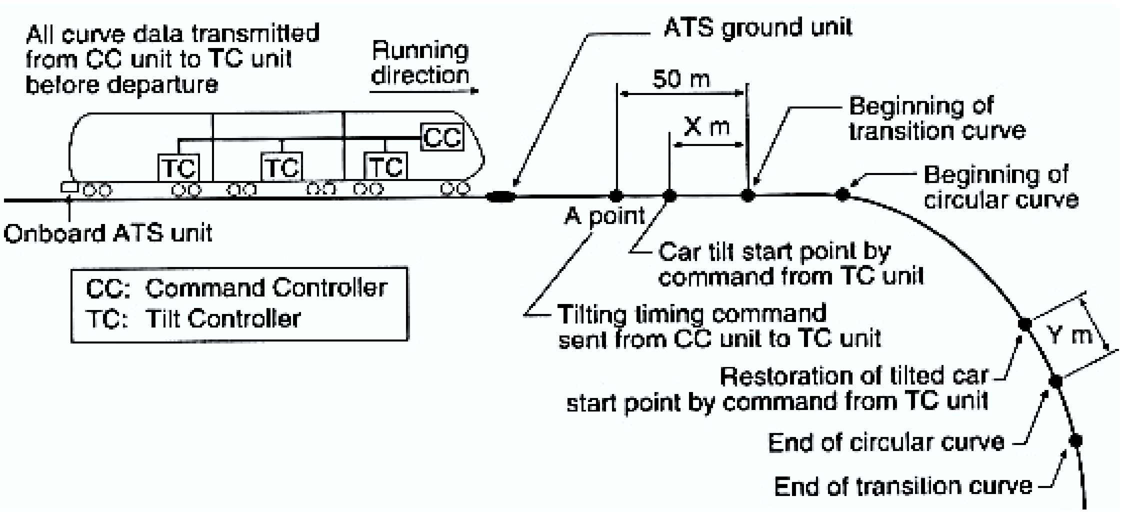

Figure 4.5 Principles of controlled tilt systems (Source: Japanese Railway Technology Today, 2001)

The on-board train computer stores all information about the curve radius, alignment, elevation, and the railway line where the train will run. Tilting the carriages start approximately from 30 to 40 metres before the carriages will enter the curve as it was found that it will reduce the passengers feeling the sense of motion sickness. Table 4.3 shows the data related to HSRS that was in operation in 2017.

Table 4.3 HSRS for selected countries in 2017 (Created by Author) Data taken from (Uic.org., 2018a)

Selected Countries with HSR	Total number of HS train sets	Average traction power of HS train sets (kW)	Total number of seats	Electric power consumption (gWh)
KR	109	10800	67524	2735
ES	229	5160	60063	2621
DE	257	6700	118698	7969
TR	13	5050	5488	217
TW	34	9600	33626	443
FR	410	8770	192813	6300
CH	2411	8960	1596810	n/a
IT	137	7410	69272	4222
JP	398	11500	376461	6525

The largest number of train sets belongs to China, which is 2411, the trains with the highest average traction power belongs to Japan whereas Germany has the highest electric power consumption.

4.4 Conclusions

For this research, ten HSRs are selected, four of them located in Asia and five in Europe and one in Turkey, 5% of territory of Turkey is in Europe and 95% in Asia. The HSR is defined as the system that operates at 250kph or more. These speeds require:

- Construction of new purpose build lines,
- Specially designed train sets,
- Special Signalling systems

Despite that HSR system is defined as a system that operates at a speed of 250kph and above many factors can affect operational speed from the condition of rolling stock to the number of stops on a route. For the selected HSRs, the average operational speed varies between 149kph for Turkey to 282kph for China.

The length of the railway network for selected countries varies between 120km in the Netherlands and 26,869km in China. The majority of selected HSRs are purpose-built lines, but Germany put lots effort to upgrade existing lines to operate at a higher speed. According to the number of passengers that was served by HSRs, China had the largest number of passengers in 2017, which was 577,635 million. Demand for travel on HSR depends on many factors, and the most important of them is the density of population and personal income.

All HSRS are powered by electricity. HSRS can have concentrated power or distributed. Most of selected countries operated HSRS with distributed power, such as Japan, Taiwan, China, Turkey, some countries have both types of rolling stock distributed and concentrated power, South Korea has concentrated powered HSRS. Also, HSRS can be articulated, tilting, and double decker. For example, France has articulated and double decker HSRS. Some HSRS in

Japan, Germany and Italy are equipped with tilting technology. Most HSRS in Spain is articulated. South Korea operates articulated HSRS.

HSR is powered by electricity but needs to take into consideration how electricity has been generated. Germany generate electricity by burning solid fuels, or France 85% of electricity is from nuclear power stations, or Sweden, where trains are powered by 100% renewable energy (hydropower and solar power). Railways can only be less environmentally polluted if they are powered by green energy.

The standardisation and harmonization of track gauge, maximum load per axle, systems of electric traction, signalling systems, and line profiles is crucial to operate effectively across Europe. The differences in railway technical standards in Europe create an additional cost for all railway systems. By reducing the number of different HSR technologies and increasing the standardisation, it will improve the safety, reduce the capital cost, and increase the compatibility of railways and in the long term will reduce the journey costs.

Chapter 5
Investigating Sustainability of High-Speed Railways (HSR) Using NVivo Analysis

5.1 Introduction

Sustainability of transport systems is an ability to continuously provide services at a level that it will satisfy the increased demand for travel by effective use of existing resources without compromising those of future generations.

Transport systems provide access and mobility for society and support economic growth. However, the environmental and social costs of transport increase. Transport has many negative impacts, such as carbon dioxide emissions, noise pollution, water pollution, local air pollution and land taken. HSR operates on the electrified network and it can be zero carbon dioxide emissions if it uses electricity from renewable sources. The sustainability of HSR depends on the relationship between HSR, carbon dioxide emissions, land use patterns, car ownership and demand for travel by HSR. Efficiency, reliability, safety, and sustainability are the main objectives for developing HSR.

In this research, many relevant papers have been studied which covered the benefits and disadvantages of developing and operating HSR systems. Several relevant variables have been found that will be analysed to evaluate the sustainability of the selected HSRs and define factors that affect such sustainability. The conclusions have been drawn based on an analysis of qualitative and quantitative data partly by employing NVivo software.

5.2 Environmental sustainability

5.2.1 Introduction

There is an urgent need to shift from roads to a more sustainable mode of transportation. The Paris conference in December 2015 agreed to set a limit of global warming of less than 2º Celsius to pre-industrial levels (Unfccc.int., 2020). To achieve this goal, there should be a substantial reduction of non-renewable energy in transportation.

Noise levels are continually increasing, and it reduces the quality of life, negatively affects health, and reduces property prices. Noise is one of the most important environmental emissions for people who are living next to railway lines. With the increase in population, the consumption of non-renewable natural resources is increasing.

Transport is one of the major consumers of natural resources and land. Building HSRs has an impact on biodiversity, there is destruction of natural areas and has a negative visual impact.

5.2.2 Carbon Dioxide emissions

The Carbon Dioxide emissions from the transport industry is projected to increase by 73% from 1985 to 2030 (Perrels et al., 2008). Table 5.1 shows the Carbon Dioxide (CO_2) emissions from the transport industry in EU15 have significant increases over the period 1990-2000 and now it is the second major contributor to Carbon Dioxide emissions after the energy industry.

Table 5.1 Total Carbon Dioxide emissions from transport, 1990-2000 (Source: Banister, 2005)

Transport-million tonnes of CO_2						
EU15	**RAIL**	**ROAD**	**AIR**	**INLAND**	**TOTAL**	**% OF ALL**
1990	8.9	625.0	82.2	19.6	735.7	23.9%
1995	8.4	675.6	96.2	20.5	800.7	26.2%
2000	7.0	762.3	126.0	15.1	910.5	28.7%

Only one transport mode, railways continually decrease the produced amount of carbon dioxide emissions. Different pollutants have different effects on the environment and people. NO_X, CO, CO_2, SO_2 and hydrocarbons are the main airborne pollutants produced by transport systems.

The railways contributed just over 1.5% of total Carbon Dioxide emissions (UIC - International union of railways, 2019c). Through high dependency on fossil fuels transport plays a major role in the increasing amount of emissions, transport produces 27% of the total world Carbon Dioxide emissions and 95% of total energy consumption comes from fossil fuels. The transport industry still increases CO_2 emissions, and it is the only industry that is not reducing (Cer.be., 2019).

Air pollution from trains can be caused in two ways, directly and indirectly. Air pollution is caused by diesel locomotives, but indirectly in the power station where the electricity is generated. Indirect pollution depends on how electricity is produced. Emissions produced by HSR depend on the source of energy supply. HSR still produces less air pollution compared to other transport modes.

HSR transport is the most energy efficient mode of transportation, and it is continuously improving their performance in terms of energy use per passenger-kilometre. By using renewable energy such as Sweden and Norway, it can offer carbon-free transportation. Targets for railways in Europe are to reduce Carbon emissions by 50% by 2050 compared to the 1990s (UIC, CER, 2015). Railways, and particularly HSR can be a solution for current transport problems, as railways are offering efficient transportation of passengers and freight, low Carbon emission, low environmental impacts, and positive economic growth.

5.2.3 Sustainability of HSRs in terms of efficient use of natural resources

5.2.3.1 Introduction

Increased globalization has a large impact on the transport system. Traffic growth is largely the result of economic growth in a such a way that when a country's gross national product goes up, personal travel increases by a factor of 1.5 in relation to the GDP. It was estimated that the average growth rate of passenger kilometres increases by 4.6% every year (Whitelee et al., 2003a).

The role of railway transport increases and is becoming an important mode of transportation because it offers many advantages over other modes of transport. Reducing the energy that is consumed by railways and reducing the amount of raw materials that is used by railways can sufficiently reduce the environmental impact of railway and improve its economical sustainability. The Carbon footprint that a train may accommodate over its life cycle can be 55 to 85% because of energy consumption whilst the rest is related to the use of raw materials (Andries, 2016).

5.2.3.2 Resource efficiency

The global economic system depends on how natural resources it uses. All-natural resources are divided into renewable resources and non-renewables such as raw materials, land, and fossil fuels. At the present time, the transport sector is the major consumer of fossil fuels and is responsible for most of the emissions of CO_2. It is stated that the UK transport sector in 2014 consumed 54.2 million tons of oil (38% of the total consumption of oil) with an increase of 1.1% from that of 2013. Considering that transport is responsible for 74% of the total transport energy consumption, air transport is responsible for 23%, the rail transport is responsible for 1.9% including high-speed trains (Waters et al., 2015). The growth of population may mean a growth in the consumption of raw materials whilst the world energy reserves, and raw materials are finite. It was forecast that oil reserves in the world would run out around the year 2040. This is only approximate, but it must be realised that oil reserves are limited. Modern transport depends 95% on fuel oil, and HSR can reduce dependency on this energy resource.

In the EU railway transport carried 11% of goods and 8% of passengers and was responsible for only 0.6% of the emission of GHG and consumed only 2% of the total energy consumption in transport (Jehanno et al., 2011). The railway network can accommodate more passengers and freight. Resource efficiency for HSR means that there is a need to minimise emissions from the construction or upgrading of the railway infrastructures, increase recyclability of train components and parts of infrastructure, and sensitively use the land resources. Reducing the weight of rolling stock will reduce the amount of raw materials that is needed to build it.

The better use of insulating materials in the construction of rolling stock can reduce energy output. Modernisation of existing high-speed trains instead of building new ones can give substantial savings in energy and raw materials. When the first generation of ICE was modernised, it gave savings of 16000 tons of steel and 1200 tons of copper (Jehanno, 2011). Further weight reductions can be achieved by replacing conventional stock by articulated rolling stock and increasing the use of aluminium and light alloy construction.

Because of the high rate of scrapped cars around the world, transport is responsible for a large proportion of solid waste. Regarding railway transport, there are abandoned lines, equipment and rolling stock. Improving recyclability by 10% in the European railway sector can produce an economic benefit of around 170 million Euros per year (Garcia, 2010). The percentages of resources that are used to produce a typical train car are depicted in Figure 5.1.

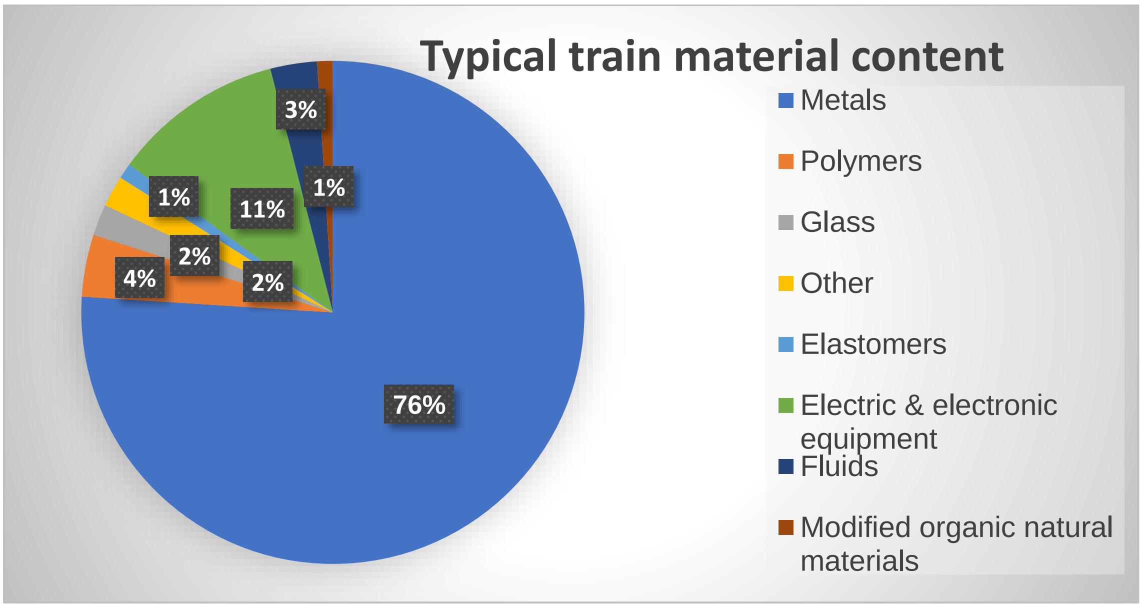

Figure 5.1 Typical train material content (Source: Amended from UIC-environment., 2019)

In most countries, recently designed trains have around 40 years of service life and this long life supports resource efficiency. At the design stage of a new rolling stock, there is a need to minimise the amount of generated waste and to avoid potentially hazardous materials such as asbestos-containing materials or substances that may contribute to the damage of the ozone layer and speed up climate change. For example, at the production stage, there is a need to re-use parts and components of the rolling stock whilst at the disposal stage of the rolling stock there is a need to recycle the greatest amount of used materials.

Bombardier's vision is to achieve 100% product recyclability and to use 100% recycled materials. At the current time, Bombardier has an average recovery rate for all manufactured rolling stock of 95%. The French AGV has 98% recyclability (Jehanno, et al., 2011). The proper disposal of the end-of-life rolling stock and components of railway infrastructure can reduce the negative impact on the environment. It was found that disposal of one freight carriage generated is the same amount of waste as 16-20 passenger road cars.

Freight rail carriages are easier to recycle than passenger carriages. 60 to 80% of their mass is Steel and Cast Iron and it is known that metals have the highest recyclability rate (unife.org., 2013). Passenger rail carriages, particularly EMUs are more difficult and labour intensive to recycle. At the present time, there is a lack of technology for recycling polymer and plastics, but it is easy and cheap to produce them. Different plastics have different chemical components, and this makes it difficult to dispose of them.

The disposal of RS is analogous to the disposal of road cars. Newport in the UK has the largest shredder in the world and can shred 450 cars per hour (weg.net., 2009). One of the most difficult issues of recycling of rolling stock is getting a rail carriage to the recycling site, as many of them in their current condition are not suitable for transportation on the main line.

The scrap value of a carriage is around £11,500 but to get it to a recycling site will cost approximately £5000 (unife.org., 2013). There is little economic benefit for the railway industry to encourage it to recycle the rolling stock. There is a need to support the railway industry in recycling the rolling stock and parts of railway infrastructure. Suitability for recycling or recovering is measured through MRF (Material Recovery Factor) and ERF (Energy Recovery Factor).

MRF represents the availability of recycling and inefficiency of the recycling processes. ERF represents the suitability of the material concerned to be recovered as energy. Values of ERF and MRF need always to consider the concept of valuating the efficiency of recycling (unife.org., 2013).

The largest manufacturers of rolling stock for HSR are Germany, Spain, Japan, and China. One example of influence on the domestic market on the rolling stock industry can be the UK. In the middle of the 1960s large parts of the railway network in the UK were closed, and that affected the railway rolling stock industry in the UK drastically.

With the creation of the EU and the single market, some changes in the RS industry occurred. RS manufacturers moved over the national boundaries and became international companies.

High demand for new rolling stock is observed in China and South-East Asia. China is the largest producer of RS in the world. In 2012-13, the top 10 manufactures of RS had 65% of the global market (Briginshaw, 2017). The two biggest manufactures of RS in China are CNR and CSR. Table 5.2 shows the ten biggest manufactures of rolling stock in the world.

Table 5.2 The ten biggest manufactures of rolling stock (Data taken from various sources)

Rollin Stock Manufacture	**Country**	**Place in the World in 2013**
CNP	China	1
CSR	China	2
Bombardier	Canada	3
Alstom	France	4
Transmashholding	Russia	5
Stadler	Switzerland	6
Siemens	Germany	7
GE Transportation	UK	8
Uralvagonzavod	Russia	9
Trinity Industries Inc	USA	10

The biggest Japanese and Spanish manufacturers of rolling stock is not presented in the top ten. High-speed trains that are presented in Table 5.3 have a large variety in terms of axle loading; from 11.4t Hitachi Train to 23t Bombardier. The large difference can be explained by the type of railway that uses this RS.

Another important feature is the power system of HSR. With a centralized power system, train has a heavy locomotive engine, and it needs that the subgrade and foundation be stronger, and it must use a stronger rail. This involves a larger amount of raw materials to build high-speed railway lines. The distributed power system is more advanced in terms of using fewer raw materials.

Table 5.3 Comparison of different high-speed trains in terms of power systems, axle loading, and car body materials (Data taken from various sources)

Country	Main Constructor	Train	Power system	Axel Loads	Car Body
France	Alstom	AGV	Centralized	17t	Aluminium with Carbon
Japan	Hitachi	Shinkansen-Series 0	Distributed	16t	Carbon Steel
Japan	Hitachi	Shinkansen-Series 700	Distributed	11.4t	Aluminum alloy
Spain	Talgo	Talgo 350	Centralized	17t	Aluminium
Italy	Hitachi Rail Italy	Frecciarossa	Distributed	17t	Aluminum alloy
Germany	Siemens	ICE1	Centralized	19.5	Aluminium-Silicon alloy
Germany	Siemens	ICE2	Centralized	19.5t	Aluminium-Silicon alloy
Germany	Siemens	ICE3	Distributed	15t	Aluminium
Sweden	Bombardier	SJ X2	Centralized	17.5t	Stainless Steel
USA	Bombardier	Acela Express	Centralized	23t	Stainless Steel
China	Bombardier	CRH1	Distributed	15t	Stainless Steel
China	Siemens	CRH3C	Distributed	17t	Aluminium
Canada	Bombardier	Zefiro	Distributed	16.5t	Aluminium

Aluminium car bodies may give raw material saving and reduce energy consumption to operate trains. Replacing steel by aluminium can achieve weight reduction of the car body of a train between 20-30%. A typical high-speed train comprises 400,000 different parts (Plm.automation.siemens.com., 2019).

5.2.3.3 Efficiency in terms of land use

Land is one of the natural resources, and as it is not infinite, it must be taken seriously as an index of a sustainable society. There is a reason to believe that land use would be a major barrier to the development of new transportation systems. HSR is environmentally less polluting and consumes less land than motorways or airports whilst some HSR routes for long distances run in tunnels. It was reported that approximately 90% of the route of the HSR in Taiwan (THSR) was placed in tunnels or on raised viaducts (Watson, et al., 2017a).

The network of HSR in the next 10 years will increase and most of it will be in countries that have developed HSR networks already. There was a plan to build 14000km of HSR in countries such as Iran, Morocco, Turkey, Argentina, and the USA. HSR can carry 12,000 passengers per hour per track, whereas a single line highway carries 2250 passenger cars per hour and HSR is approximately 5-6 times more efficient than road transport in terms of land use (Agarwal, 2011).

Building HSR will need more land take than that required to build a conventional line, as HSR needs to allow greater distances between the railway tracks. The reason for this is the pressure caused when two trains pass each other with a speed of 250-350kph. Also, HSR requires larger radius curves than conventional rail. Table 5.4 shows the selected corridors of HSR and the types of line in those corridors.

Table 5.4 Comparison of different corridors for HSR in terms of minimum radii of curve (data taken from various sources)

Country	Corridor	Length km	Track	Type of Line	Radii of Curve m	Track Gauge m
Japan	Tokyo -Osaka	515.4	Double	Dedicated	Minimum 2500	1,435
France	Paris-Lyon	425.0	Double	Dedicated	Minimum 4000	1,435
Spain	Madrid-Barcelona	620.9	Double	Dedicated	Minimum 7000	1,435
Italy	Rome-Florence	254.0	Double	Dedicated	Minimum 3000	1,435
Germany	Cologne-Frankfurt	177.0	Double	Dedicated	Minimum 3,350	1,435
Sweden	Stockholm-Gutenberg	455.0	Double	Mixed Line	n/a	1,435
USA	Washington C.D. -Boston	729.5	Double	Mixed Line	Absolut minimum 76	1,435
China	Beijing-Shanghai	1,318.0	Double	Dedicated	Minimum 7000	1,435

Horizontal and vertical curves are important parts of railway alignment. Minimum radii of curves depend on the maximum speed of the rolling stock, technical characteristics of the RS, topography of corridor, safety standards, and constructional and operating costs. Large radii of curves are more comfortable for passengers to travel. New HSR lines built with a minimum curve radius of 7000m will allow railway speeds of up to 350-400kph.

The amount of land needed to construct HSR depends on the geographic region and specific needs of the project. Also, there is a need to strike a good balance between the needs of the project and the local communities. The amount of land taken by an HSR depends on certain factors, such as is it a new railway line or upgraded one, is it a single or double track line, what is the maximum speed, size of embankments, radii of curves, etc. The amount of cutting and embankments can influence the amount of land that is needed to build HSR. Embankments reduce the noise level, but the negative impact is that it reinforces the separation effect and reduces the available living space. For example, in the proposed project of HS2 in the UK, for deep cuttings and higher embankments, a safeguarding corridor of 70m from the central line was suggested. The safeguarding boundaries can be wider for deeper cuttings and higher embankments (GOV.UK., 2019b).

Newly constructed high-speed lines are designed with a minimum of a 7,000m curve radius but sometimes the radius would need to be 10,000m to accommodate higher future speeds and to improve the passenger comfort (Revolv, 2017). Higher speed means more land is needed and more distance between centres of the main tracks, such as the case of 4.2m used in Tokyo-Osaka line. For a speed above 300kph, the UIC recommended a minimum value of 4.5m distance between track centres. The land-use and environmental impacts can be minimised by placing railways in tunnels and on viaducts.

5.2.3.4 Efficiency in terms of energy consumption

Railways have a significant advantage over road and air transport, as electrified railways can use different energy; nuclear, wind, solar, water, oil. The energy consumption of a high-speed train depends on a few factors including technical characteristics of train, layout of line and several stops. The number of curves and their radii and length, the gradients of line and other factors can affect the train energy consumption. Reducing the number of curves can increase the speed of a train and uses less energy.

Using regenerative brakes, high-speed trains can recover some energy dissipated by braking, and this energy can be used by other trains or can be returned to the power network. Improving the aerodynamics of trains can sufficiently reduce energy consumption. Also important is the electric system that the railway line is equipped with. There is an energy loss during the transmission and transformation from the power station to the train. There is a big difference in the losses for high-speed lines electrified at 25kV and at 3kV as the loss for a line voltage of 25kV is lower than 3kV. There is a need to provide 8.8% more electricity through a pantograph to operate a train at 25kV compared with 22.6% to operate a train at 3kV (Garcia, 2010).

Two main factors determine a train energy consumption: namely, acceleration and overcoming rolling resistance. New high-speed trains have improved design to reduce drag, increase capacity, and use lighter materials that reduce the weight of the train. The new articulated high-speed train AGV from Alstom has a reduced weight and needs 15% less energy than that of TGV and has 98% recyclability (Bombardier Transportation., 2019). Power output for high-speed trains also depends on a train formation. Trains can have different formations from 16 or eight cars as has Shinkansen Series 500 and Shinkansen Series 700 or the 8 cars that Frecciarossa has. Some trains are more flexible in formation, as AGV can be formed from seven, eight, 10, 11 or 14 cars.

Reducing the axle load is the most critical factor in increasing the speed of trains and reducing energy consumption. This can be achieved by introducing the articulated railcars and using a new lighter material. For TGV, Duplex car bodies, aluminium was used which is easy to recycle and it does not lose its quality after recycling. To increase the passenger-kilometres carried per unit of energy, there is a need to consider the number of seats, so that instead of having locomotive and passenger cars, these can be replaced by electric multi units. Figure 5.2 shows that the lowest energy consumption belongs to the Shinkansen rolling stock.

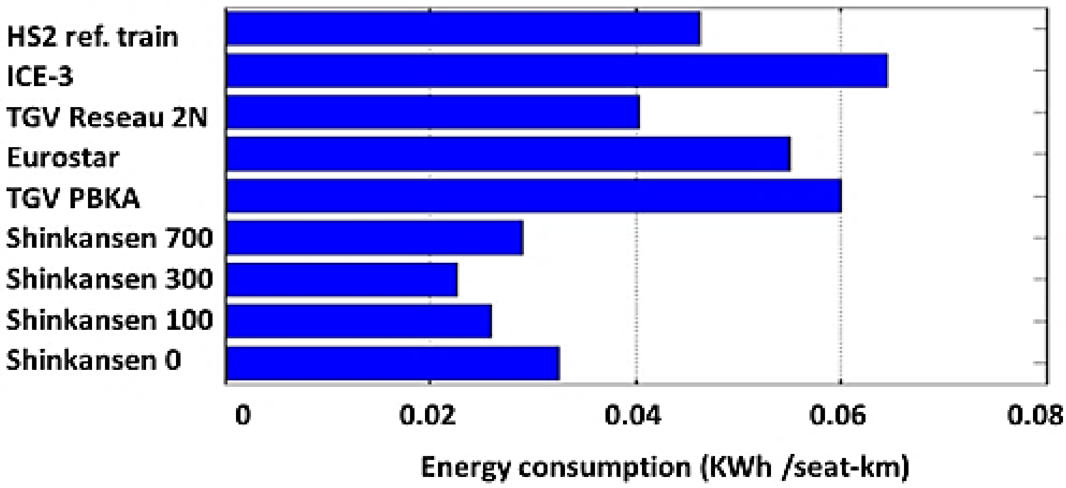

Figure 5.2 Comparison of net energy for HS trains (Source: Watson R., 2012)

One explanation for this is that in Japan, rolling stock is renewed to a more efficient type every 15-20 years. Newer high-speed rolling stock has an improved design, reduced drag, increased capacity, reduced axle load, improved energy efficiency and upgraded passenger comfort to meet changing customer expectation. Trains in Europe are designed for 30-40 years' service life. Table 5.5 shows the comparisons of different HS rolling stock in terms of speed, power output and type of trains.

Table 5.5 Comparisons of different high-speed rolling stock in terms of speed, power output and type of trains (data taken from various sources)

Train	Maximum Speed Kph	Power output	Type of train
AGV	360	5,760 kW	Electric multiple unit
Shinkansen- Series 500	300	18,240 kW	Electric multiple unit
Shinkansen-Series 700	270	13,200 kW	Electric multiple unit
Talgo 350	330	8,000 kW	Two Power Cars
Frecciarossa	300	9,800 kW	Electric multiple unit
ICE1	280	9,600 kW	Two Power Cars
ICE2	280	4,800 kW	One Power Car
ICE3	330	8,000 kW	Two Power Cars
SJ X2	200	3,260 kW	One Power Car
Acela Express	240	9,200 kW	Two Power Cars
CRH1	200	5,300 kW	Electric multiple unit
CRH3C	350	8,800 kW	Electric multiple unit
Zefiro 300	360	9,800 kW	Electric multiple unit

The using more advanced rolling stock can increase speed and reduce energy consumption.

5.2.3.5 Conclusions

There are many ways to achieve the targets for sustainable mobility. Such achievements can be made possible through a greater technological improvement. The HSR and railway industry is working to improve efficiency, reduce the weight of vehicles, and develop new technologies to reduce the power needs for the industry. Despite the increasing speed of modern trains, energy consumption is reduced by 25-45% (Lukaszewicz & Andersson, 2008). The assessment of transport efficiency must be related to the total energy life cycle, from the extraction of the minerals to their final return to earth as waste. For example, on average, the Alstom train is 93.3% recyclable and 98.5% recoverable, and there is a future need to increase the recyclability closer to 100%.

To reduce the amount of raw materials used in the railway industry, manufacturers are continuously working to minimise waste and to increase recycling and energy recovery. This can be achieved by improving the recyclability of the rolling stock and infrastructure and by increasing the use of the amount of materials that is being recycled. For instance, the recoverability of TGV Euroduplex is 97-98% (Andries, 2016).

5.2.4 Negative impact from noise and vibration

5.2.4.1 Introduction

Often the most obvious form of pollution from transport is noise. Noise is one of the most important environmental emissions for people living next to railway lines. Noise and vibration generated by trains increase with the increase in speed. The basic unit used to measure sound or noise is the Decibel or dB(A). People are more sensitive at higher frequencies than to lower frequencies (Wolf, 2010). The biggest concern about HSR is the amount of noise produced by trains and the number of people who may be affected by it. Until recently, the most popular method to reduce noise was to use noise barriers and to insulate windows.

5.2.4.2 Factors affecting noise level

The noise generated by HSR can be less than the noise from a conventional line with mixed traffic. Many factors can affect the noise level, it can be the age of the infrastructure and materials that have been used to build the track, level of maintenance, rolling stock and how the railway is operated. If a railway track is in a poor state and has a low level of maintenance, then it would emit 10dB(A) more than a new one (Transport Policy and the Environment, 1990). Table 5.6 shows that there is a strong relationship between noise level and speed.

Also, there is a strong relationship between noise level and distance to the receiver and between noise level and infrastructure type. The noise level was influenced more by the distance than by changes in speed. To reduce noise level propagation, it is more effective to put the railway line in cuttings, but such a solution can be expensive.

Table 5.6 Maximum and registered noise emissions of existing high-speed trains (Source: Clausen et al., 2012; Feilden et al.,1995)

Speed in km/h	Maximum noise emission according TSI NOISE in dB(A)	Current emission of German HS Trains in dB(A)	Difference in dB(A)
200	n/a	>80	n/a
250	87	87-94	0-7
300	91	91-95	0-4
320	92	92-96	0-4

TSI NOISE- European Railway Technical Specification for Interoperability for Noise defines the maximum noise levels for RS. For high-speed trains, noise level emission is a big concern. For the German ICE with a speed of 200kph, at 25 metres from the track it was recorded that the noise level was over 80dB(A), and at a speed of 300kph the noise level was around 90dB(A) (Feilden et al.,1995). This is a major problem for many countries, where the railway tracks pass densely populated areas. Doubling speed will increase the aerodynamic noise level by 18dB (La).

Many elements contribute to the total noise emission from trains including pantograph noise, aerodynamic noise generated by the car bodies, running noise generated from the underbody and noise from concrete structures. Pantograph noise comprises aerodynamic noise generated at the pantograph and pantograph shield, friction noise is caused by the collector running on the catenary and sparking noise between the collector and catenary.

Aerodynamic noise generated by the airflow over the carriage is only relevant to high-speed trains (Martens et al., 2018). To reduce the negative impact of pantograph noise, but cables were installed between pantographs to reduce sparking noise. Even if one pantograph bounces off the catenary, current still flows through the other pantograph, preventing sparks. Reducing the noise from the car body can be achieved with smoother surfaces of cars. Figure 5.3 shows the major exterior noise sources on high-speed trains, which are aerodynamic, pantograph and wheel-rail interaction noises.

Figure 5.3 Major exterior noise sources on high-speed trains (Source: Adapted from Dewberryjes.blogspot.com., 2019)

These noise sources are speed dependent. Traction noise, which is generated by the electric traction system, is distributed between the bogie height and the roof of the train. Noise from the cooling system will be the dominant traction noise (Zhang & Jonasson, 2006). The level of traction noise varies for different locomotives or EMUs and for different operational conditions.

Noise from wheel-rail interactions depends on the wheel and rail roughness and on the speed of the train. This type of noise can be partially mitigated by rail grinding. Aerodynamic noise becomes more important for HSR trains than the rolling noise (Zhang, 2010). It comprises noise generated from the pantograph, noise of the train, roughness of the RS body and gaps between cars, etc. Intensity of aerodynamic noise pollution depends on train speed.

Modern HSRS has metal panels on top of the coaches to improve the aerodynamic profile of coaches and pantograph. The pantograph is important as it is not sheltered by noise barriers. The number of pantographs needed to collect the current for the train set could be reduced, and as a result, this would reduce the aerodynamic noise sources. This noise is insignificant for low and medium speed (V<200kph), important for high speed (200<V<300kph) and dominant for very high speed (V>300kph). Mechanical noise is dominant at low speed, wheel-rail interaction noise is dominant at speeds up to 300kph whilst the aerodynamic noise is dominant at speeds of over 300kph (Giesler, 2011). The modern HSRS in the majority has a distributed power system that reduces noise emissions. However, a distributed power system increases the noise level inside the coaches. People inside the train are affected by different noises; traction noise, rolling and aerodynamic noises. Table 5.7 shows the HSRS in selected countries.

Table 5.7 HSRS in selected countries (Source: Amended from Uic.org, 2018a)

Country	Owners or Operators	Class	Train set Formula	Type of power
France, Belgium, UK	Eurostar	373 e300 TGV-TSMT	2 Locomotives 18 Trailer Coaches	Concentrated
France, Belgium, Netherlands	Thalys	Thalys PBKA	2 Locomotives 8Trailer Coaches	Concentrated
Germany	DB AG	401(ICE1)	2 Locomotives 12 Trailer Coaches	Concentrated
Germany	DB AG	403(ICE3)	4 Motor Coaches 4 Trailer Coaches	Distributed
Italy	Trenitalia	ETR460	6 Motor Coaches 3 Trailer Coaches	Distributed
Italy	Trenitalia	ETR500	2 Locomotives 12 Trailer Coaches	Concentrated
Spain	Renfe	S102	2 Locomotives 12 Trailer Coaches	Concentrated
Spain	Renfe	S103	4 Motor Coaches 4 Trailer Coaches	Distributed
China	CR	CRH1A	5 Motor Coaches 3 Trailer Coaches	Distributed
China	CR	CRH2G	4 Motor Coaches 4 Trailer Coaches	Distributed
Japan	JRW	500-7000	8 Motor Coaches	Distributed
Turkey	TCDD	HT65000	4 Motor Coaches 2 Trailer Coaches	Distributed
USA	Amtrak	Acela	2 Locomotives 6 Trailer Coaches	Concentrated

With increasing speed, the noise inside the train cars increases (Soeta et al., 2013). For HSR, the noise from the bogie area has a larger impact on interior noise than aerodynamic noise. EMUs have traction motors that are located beneath the passenger saloon. The floor of passenger carriages must be sound proofed (Zhang et al.,2016). Passenger cars must be designed to reduce noise inside the passenger saloon by using advanced materials and suitable designs. The car bodies with shielding and acoustical absorption can provide cost-effective noise reduction. Countries such as Japan, China, and Turkey have only

HSRS with a distributed traction system, but the USA uses rolling stock with a concentrated traction system. Countries in Europe, such as Italy, France, Spain, Germany, and UK, have rolling stock for HSRs with both types of traction systems; distributed and concentrated.

A significant contribution to noise level is the interaction between wheels and rails. The roughness of the wheel and rail generates the rolling noise when the wheel travels along the rail, but it also depends on the load and speed of the train. Articulated trains have a less effect of running noise on passengers (Japanese railway technology today, 2001). Wheel and rail rolling noise are proportional to the third power of train speed (Lynch, 1998).

To reduce this negative impact of running noise, different types of wheels were developed: solid wheels, resilient wheels and wheels provided with constrained layers. The most common is the solid wheel which is used for high-speed trains. It comprises a single steel part, but sometimes layers of viscoelastic material are placed between the web and a stiff constraining plate to reduce wheel noise emission (Scott, 2009). The railway insulation pads that are placed between the rail and sleepers can sufficiently reduce the noise level radiated by the track.

The track, and the surface of the rail can make a difference by more than +/- 10dB(A). Also, buildings and civil engineering works can affect noise levels or amplify or attenuate such levels (Feilden, 1995). There are measures to mitigate the rail-wheel noise, including rail lubrication, grinding, noise barriers, damping, etc. The most-cost efficient one is the reduction of roughness of rail by rail lubrication and grinding (Tuler et at., 2017). To reduce the noise level from the contact between the wheels and rail, wheel-track absorbers can also be used. This potentially reduces noise level between 1 to 3dB(A) (Oertli et al., 2010). Mitigation of wheel noise is a difficult task as wheels interact not only with the rail but also with the substructure.

Today, HSR often uses ballastless tracks such as a concrete slab-track. This rail support is not good for reducing noise and vibration emissions (Sheng et al., 2017). Concrete structure noise is proportional to the second power of train speed. Embedding a viscoelastic material can reduce the level of noise emission from ballastless track. To reduce the noise level from the concrete, grooved slab mats can be placed in the general area of the rail (Japanese Railway Technology Today, 2001).

5.2.4.3 Measures of reduction in noise level

There are three ways to reduce noise: at the source, around the noise source and at the receiver end. The decision-making process concerning the layout of railways is the most efficient stage for the reduction of noise and vibration. The corrugated track can increase the noise level between 10dB(A) and 20dB(A) (The Railways Challenges to Science and Technology, 1995).

Elevated rails along the top of embankments, bridges and viaducts propagate noise over long distances and result in noise levels at a range of 75÷105dB(A). Stiff embankments can be a source of high frequency vibration (Connolly et al., 2014). Many techniques for reducing noise at the source have been developed such as improving the infrastructure and rolling stock design, traffic management, using preventative maintenance, acoustical rail grinding, rail dampers, etc. Increasing the operational restrictions and reducing the number of trains using the line will reduce the level of noise.

There are various measures to control noise along the railway line, including noise barriers of various heights. Noise barriers can reduce the noise level between 5 to 15dB(A) (Oertli et al., 2010). Usually for railways 2-metre-high noise barriers are used, but for HSR it needs to be 4 meters or more, as a high proportion of noise come from pantographs (Transport Policy and the Environment, 1990). The height of trains varies from 3.36m for S102 type train to 4.32m for Acela train. The width and height of trains influence the aerodynamic performance of running trains.

Pantographs are especially important because they are located on the roof of trains and not so much sheltered by noise barriers (Iglesias et al., 2017). In some cases, due to the topography nature of the area where a railway line is passing, it can be necessary to use cuttings and tunnels.

Railways have a long tradition of tunnels, as many HSR lines were constructed in long tunnels. The 327 km Hanover-Wurzburg line in Germany includes 62 tunnels totalling 118 km (Transport Policy and the Environment, 1990). Tunnels can reduce noise levels, but they can also generate noise.

To minimise noise level from railway tracks, it is good to keep the level of rails as low as possible as the ground and vegetation attenuate the occurring sounds. However, with the changing climate and increasing extreme weather events there is a need to consider future possibilities of flooding for which the elevation of rails on top of embankment can become a necessity.

Measures to reduce the noise level inside a building are double or triple glazing and acoustic insulation. It is important to provide measures to reduce noise levels in buildings at the design stage. Every doubling in distance from the HSR to the recipient will reduce the noise by approximately 3 to 4.5dB(A) which depends on the ground condition i.e. soft ground with vegetation or hard surface covered by concrete or asphalt (Wolf, 2010). Insulation inside the building can reduce the noise between 5 to 30dB(A) (Jehanno, 2011). The most significant and sustainable lowering of the noise level can be achieved by a combination of RS and infrastructure related measures which will facilitate reducing the needs of noise barriers.

The surrounding areas of railway stations are exposed to a higher noise level. The changes in train's speed, acceleration and deceleration have a considerable impact on the resultant noise level (Džambas et al., 2018). To reduce the noise levels, absorbent material can cover station furniture, trackside walkways, and walls. Table 5.8 shows some characteristics of selected HSRS, noise values and density of population in selected countries.

Table 5.8 Comparison of selected HSRS, maximum operational speed, noise values and density of population (Author creation, Source: Poisson et al.; Uic.org, 2018; Worldometers.info, 2018)

Country	Class of Train	Max Oper. Speed, kph	Max Axle Load, ton	Train Width, mm	Train Length, m	Pass-by Noise Values, dB(A)	Density of Population by Country, P/km²
France, Belgium, UK	373 e300 TGV-TSMT	300	17	2814	394		119 380 275
France, Belgium, Netherlands	Thalys PBKA	300	17	2904	200	90-92	119 380 507
Germany	401(ICE1)	280	19.5	3020	358		236
Germany	403(ICE3)	300	16	2950	200	89	236
Italy	ETR460	250	13.5 (unload.)	2800	237		202
Italy	ETR500	300	17	2860	354	90.5	202
Spain	S102	300	17	2960	200, 244		93
Spain	S103	300	<17	2950	200		93
China	CRH1A	200	16.5	3328	213,5		151
China	CRH2G	250	15.45	3380	201,4		151
Japan	500-7000	285	N/A	3380	204		349
Turkey	HT65000	250	N/A	2920	158,5		106
USA	Acela	241	23	3175	203		36
TSI Limits		**300**				**91**	

With the increasing wealth society is getting less tolerant to noise pollution, and mitigation measures are getting more expensive. Most people affected by railway noise live in Western and Central Europe, primarily in Germany, Italy, Switzerland, France, and Belgium. Approximately 60% of the population affected by noise are in Germany and France, and the highest level recorded was along the south-north corridor Genoa-Rotterdam (Vos, 2016). Railways around the world spent a substantial amount of financial resources to reduce or mitigate noise pollution from railways.

One of the long-term goals of the German DB Railway is to cut noise emissions by half by 2020. The total cost of this will be €2.3 billion, including noise barriers and double-glazed widows. France will invest €193 million in noise barriers and rail dampers (Clausen et al., 2012). The cost of noise varies between 0.1 and 0.5 percent of Europe's GDP (Banister, 2000). Approximately €150-200 million will be spent in Europe annually on noise barriers and window insulation (Oertli et al., 2010). Increased cost of noise pollution can sufficiently affect the economic sustainability of HSR.

5.2.4.4 Magnetic field

Electric railways and high-speed railways particularly open many opportunities to increase speed and capacity for transportation, but they also have some negative impact on human beings. One of the negative impacts is the magnetic field. There was a link found between magnetic fields that was produced by electrified trains and some health problems. Trains with higher speeds produce a higher frequency of the magnetic field. There is a need to develop measures that can reduce the negative impact on health from high-speed railway transport.

5.2.4.5 Conclusions

Reducing the level of noise from railways will require substantial investments, new quieter technologies, and new noise absorbing materials. Reduction of noise can be achieved through regular maintenance of infrastructure and RS and through law enforcement concerning noisier trains. Improved designs of rolling stock can reduce the amount of noise pollution from the engine, air-conditioning, and ventilation systems. Reducing noise from 72dB(A) to 52dB(A) in an average daily noise level will produce an annual saving of about €158 per person (Micheli et al., 2016). The future development of HSR transportation systems must consider railway noise emission reduction as one of the most important goals for developing sustainable HSR systems.

5.2.5 Conclusions

The environmental sustainability of transport systems depends on the levels of pollution that is created and the efficiency of non-renewable natural resources utilization. HSRs, the same as other mass transportation modes produce pollution and use non-renewable natural resources. In this research, several relevant papers have been analysed that covered the impact of HSR systems on the environment. Major variables have been identified that relate to the environmental sustainability of HSRs. These variables will be considered for further analyses and is combined in Table 5.9.

Table 5.9 Variables related to environmental sustainability of HSR that will be considered for further analysis

Annual electric power consumption
HSR traffic
Average traction power of train
Number of HS train sets
Total number of seats
Average number of seats per train

5.3 Economic sustainability of HSR

5.3.1. Introduction

Economic sustainability is a continuous growth of economic production indefinitely. To be economically sustainable, HSRs need to cover fully (including external costs) all costs and need to reduce public subsidies to zero. The greatest amount of external costs is attributed to congestion, accidents, noise, air pollution and climate change. The HSRs have an excellent safety record, fatality rate is equal zero (Docplayer.fr., 2019). The safety record for HSRs is partly the result of better staff training, investment in HSRS and signalling systems. Billions of passengers have travelled with virtually no fatalities on high-speed trains.

With increasing wealth, consumers become more demanding on quality of the transport services, and the reliability of transport becomes more important (Nunen et al., 2011). The reliability of HS trains involves a punctuality of departure and no delays in arriving. Passengers valued reliability next after their safety and with the growing of personal income, there will be higher expectations for reliability. Reliability, safety, comfort, and service frequency for passengers are more important than speed.

5.3.2 Comparison of different HSRs in terms of punctuality

The Tokaido Shinkansen HSR in Japan is the most reliable HSR in the world. An annual average delay for the Tokaido Shinkansen is 0.6 minutes/per train. These included delays caused by natural disasters, such as earthquakes. In Japan, delays are classified if a train arrived over 1 minute later, in Europe delays are classified if trains arrive 15 minutes later than scheduled time (Denis, 2013). Shinkansen line has a very high density of trains, 13 trains per hour. The maximum density for HSR at this moment with current signaling systems is 15 trains per hour. Reliability of high-speed trains in Japan, South Korea and Taiwan is very high, this is because of dedicated HS lines, using tunnels and viaducts, advanced signaling systems and excellent training of staff.

In France, new HS lines were designed to avoid tunneling, this gives the benefit of the possibility to implement double deck trains. The big achievement of the HSR system in France is that the TGV system is compatible with existing conventional railways. However, if high-speed trains use the sections on upgraded conventional lines, it will affect the punctuality of the railway service. TGV trains use the upgraded conventional rail in the less crowded connections and for accessing major cities where construction of new high-speed line would be excessively high. Punctuality ratio in 2016 was 89.3%.

Germany had some problems with constructing HSR caused by topographical specific, dominated by mountainous terrains. Germany's railway infrastructure was upgraded, instead of building new dedicated lines only for high-speed trains and serving passenger and freight traffic. It is a multi-purpose railway network. Train delays in Germany have increased by almost a third since 2009. The reason is the huge amount of maintenance and modernization of the existing railway network. There are also many speed restrictions related to the condition of the existing railway network, and because of this, there is an increased density of traffic. Delays undermine the line capacity. In 2011, only 32% of long-distance trains arrived on time, and three out of four high-speed trains were delayed (Welle, 2001).

Spain's high-speed network is one of the widest in the world, but the total traffic is small compared to the Shinkansen and TGV. The punctuality of AVE is one of the best in Europe. High-speed trains in Spain claimed 99% punctuality in 2014 (Olive Press News Spain, 2019). To achieve this level of punctuality for AVE was easy enough, as the railway lines have a low-density traffic, and it has dedicated high-speed lines. To reach this level of punctuality for Germany or Sweden would be more difficult as their high-speed trains use mixed traffic lines. If Renfe, high-speed trains in Spain arrive just five-minute late passengers will have a full refund for that journey.

HSR in Italy is integrated with conventional lines, this increases railway network capacity, increases the effects of HSR and preventing the deterioration of the conventional services, but it affects the reliability of services. In Italy, after the year 2000, conventional railways had digressed in passenger numbers, but the number of passengers that use the HS lines is steadily increasing. In 2010, HSR had 25% of total rail traffic (Pedro, 2014). The meaning ‘on time’ for Trenitalia if trains arrived from 0 to 15 minutes of schedule time. It is difficult to compare the punctuality of different train operators, as in different countries punctuality is measured differently.

For example, ‘on time’ for SBB train operator in Switzerland that is an interval from 0 to 5 minute in the schedule time, in Austria, train operator OBB train ‘on time’ that is, if trains arrived from 0 to 3 minute of the schedule time. Overall, the punctuality of passenger train in Europe is around 93% using a 5-minute punctuality (European commission, (2012). In France, ‘on time’, counts if trains arrive less than a 5-minute delay in the schedule time for journeys of less than 1,5 hours, less than a 10-minute for a journey between 1,5 and 3 hours and less than a 15-minute delay for journeys beyond 3 hours (De Consommateurs, 2017). In Korea, ‘on time’ means if a train arrives within five minutes of the schedule time (Korail, 2010). The differences in what can be classified ‘on time’ make it difficult to compare performance of HSR in terms of reliability.

In China, nearly one billion people travel by HSR every year. In 2015 the HSR network in China reached over 19000km, with the maximum operating speeds up to 350km/h and has over 4200 high-speed trains (China.org.cn., 2017). By 2013, HSR in China carried around 2.5 times more passengers than in Japan (Ollivier, 2015). Punctuality of high-speed trains for departure in China in 2015 was 98.8% and 95.4% punctuality for arrival at the destination (China.org.cn., 2017).

The difference of THSR (High-Speed Rail in Taiwan) from other HSR is that THSR network almost 90% of the route is running either in tunnels or raised viaducts. This is because of topographical features such as steep gradients in the terrain (Mahmoud et al., 2012). Some lines in Taiwan have 56 services daily. With a maximum speed of THSR up to 190mph and with the increasing stresses on the brakes and wheels and on infrastructure, there is a need for additional requirements for maintenance to provide a high level of performance. The frequency of services and operating distance of the railway network affect the reliability of HSR service. THSR has an excellent performance regarding punctuality and average delays per train is 0.216 min/train (2009) with a frequency of 5 trains/h. THSR has a much lower frequency than Shinkansen that has 13 trains/h (Amos et al., 2010). The signal and interlocking system failure is the most common reason for train delays worldwide (Jong et al., 2010).

KTX-High-Speed Rail is in South Korea, it opened for service in 2004, and traffic steadily increased on average by 11% every year. Over 300,000 passengers use the railway every day (Media, 2017). There is in operation 412km of infrastructure and up to 92 trains run daily in each direction with designed speeds of 350kph. HSR in South Korea carry over 100,000 passengers daily, KTX accounts for over 50% of total rail traffic (Railway-technology.com., 2017).

KTX trains are fitted with the automatic train control system, which allows increases in the capacity of existing lines, reduces energy consumption, and improves the safety of railway services. This system automatically adjusts actual train speed. Trains equipped with in-cab signaling system that inform drivers about signals ahead and it also informs the main control centre about the location of trains in real time.

In the Netherlands 2015 punctuality of HSR was 94.2% (Table 5.9) and it was a huge improvement from 2007, when punctuality of the railway system was 80%. It was presumed that trains arrived on the scheduled time if delays were less than 3 minutes. However, the punctuality gauge does not give information for the length of delay (Nunen et al., 2011). Unreliability of departures are not accounted for and does not consider the travel time variation.

UK has 113km of HSR in operation, and it is planned to build another 204km. In 2014, the number of passengers reached 10.4 million (Ltd, 2015). In 2015, the number of Eurostar high-speed trains fell by 17% to 2421, as night-time services had been suspended from June to October because of people trying to board trains illegally (Topham et al., 2016). In 2015, 81% of Eurostar trains arrived within five minutes of their scheduled arrival time, it is down from 2014 which was 83.8%, and 90.2% of trains arrived within fifteen minutes of their scheduled arrival time (Eurostar, 2016). Eurostar received almost 20000 complaints about train delays for the same period. Table 5.10 shows the comparison of performance of HSRs in the selected countries.

Table 5.10 Comparison of performance of HSRs in the selected countries (Source: Author's creation)

Name of country	**Satisfaction with punctuality and reliability (2013)**	**HS traffic pass.km. (billion)**	**Punctuality ratio**	**"On time" If train delay no more than**	**Train operator company**
Japan	n/a	90.280 (2015)	98.3% (2005)	0- 1min	Shinkansen
France	62% (2013)	49.976 (2015)	89.3% (2016)	0- 15 min	TGV
Germany	53% (2013)	24.316 (2015)	94.8% (2015)	0-15 min	DB
Spain	84% (2013)	14.129 (2015)	99.6% (2010)	0-5 min	Renfe
Italy	48% (2013)	12.794 (2015)	97.3% (2014)	0-15 min	Trenitalia SpA
China	n/a	214.00 (2013)	95.4% (2015)	n/a	CRH
Taiwan	n/a	8.642 (2012)	99.66% (2015)	n/a	THSR
South Korea	92.6% (2010)	9.937 (2008)	99.8% (2009)	0-5 min	KTX
The Netherlands	66% (2013)	0.915 (2008)	94.2.0% (2015)	0-3 min	NSL South
United Kingdom	81% (2013)	1.130 (2015)	90.2% (2015)	0-15 min	Eurostar Intl

To reduce the delay time, there is a need to improve traffic management in cases of delays and disruptions. In situations when disruptions occur the lack of information leads to much discomfort for commuters (Nunen et al., 2011). Implementing the Real-Time Passenger Information systems on board trains and at railway stations could reduce distress for commuters.

The disruption management should quickly provide a modified timetable, rolling stock circulation, and crew duties (Nunen et al., 2011). The main measures to raise the reliability would be to improve the engineering facilities and the staff skills to manage better occurrences of train delays.

5.3.2.1 Correlation between punctuality and accident rate

According to the European Rail Agency's report, 2013, in the EU on average every year around 2400 significant accidents are registered on railways. More than 1000 people died in these accidents and many more injured (European Commission, 2013b). In 2014 in the EU there was registered 2213 serious accidents on the railways. There were a total of 1928 people, which had fatal or serious injuries, up by 9.5% in 2013. Moving rolling stock caused most accidents which was 1196 and the next highest number of accidents is 638 which involved level-crossings (Eurostat, 2016). Table 5.11 shows the rail traffic performance and the number of significant accidents in the selected countries in 2014.

Table 5.11 Rail traffic performance and the number of significant accidents in the selected countries in 2014 (Source: Amended from Eurostat, 2016)

Country	**Tonne-kilometres (million)**	**Passenger-kilometres (million)**	**Total number of accidents**	**Total number of persons killed or seriously injured in accidents**
France	32 217	89 499	177	140
Germany	112 629	89 120	388	302
Spain	10 821	25 146	55	42
Italy	20 072	49 957	131	113
The Netherlands	6 169	20 005	27	19
United Kingdom	22 143	64 711	70	34

Germany has the highest number of accidents in EU-28 in 2014, which were 388 accidents. The biggest amount of accidents is related to level-crossings or RS. The deadliest HSR accident happened in Germany in 1998 when 101 people lost their lives and around 100 more were injured (Akkoc, 2016). It was caused by a technical fault of the RS. This accident happened when the HS train used the conventional rail section at a speed of 200kph. The major reason that Germany has such a high accident rate is that Germany's railway network is the mixed lines where all categories of trains, including HS trains and freight trains can use the conventional lines, and it has a very intensive traffic use. There is some correlation between punctuality and accident rate and accident rate and traffic performance. For example, Shinkansen HSR in Japan holds an excellent no accident rate, there have been no fatal accidents since 1964 when it was first opened for service. Special measures can explain this, such as fenced tracks, absence of level crossings, dedicated railway line and excellent trained staff. High percentages of accidents are caused by trains running late. Improving the reliability of railway services, it will improve safety, too. Improving the reliability of railway services will lead to higher satisfaction levels of passengers and will increase the number of passengers. Quality improvement of railway services leads to an increasing number of passengers, and this will decrease the number of people travelling by road or air. Punctuality of railway services is one of the major attractions for passengers as roads and airports get congested and are difficult to plan for passenger travel time effectively. High rates of punctuality not only increase the capacity of rail lines and attract more passengers. Table 5.12 shows a summary of measures for improving reliability of HSR.

Table 5.12 Measures for improving reliability of HSRs (Source: Author's creation)

Measures	Benefits from implementing	Countries with the best practises	Costs
Dedicated double track	High capacity of line, high punctuality ratio, easier maintenance than for mixed lines, better resilient to disruption than single track lines.	Japan, Taiwan	High cost
Implementing preventative maintenance	Reduce maintenance time and cost, maximise the time of track and rolling stock availability, increase reliability of services, improve safety	Taiwan, Italy	High cost
Modern signalling systems and traffic control systems	Increase capacity of line, improve safety and reliability of services, reduce the maintenance and construction costs	Italy. Japan	Moderate
Digitalising traffic management and timetabling	Minimize the traffic disruption and capacity restriction if accidents, improve the resistance of the railway network, reduce train delays,	The Netherlands	Moderate
Improving the staff skills	Increases productivity of employees, improve safety and punctuality of railway services	Japan, Taiwan	Low

5.3.2.2 Conclusions

Analysing the performance of HSR worldwide, some common conclusions can be drawn that make one railway perform better than other in terms of reliability. The most punctual HSR has a two-track dedicated line (Shinkansen, THSR). The entire length of the track is secured by fences and screens to prevent any access to a line and no level crossings. These measures prevent any outside disruption of traffic.

Signal failure and interlocking failure are the major reasons for a train delay. Implementing advance signaling systems such as ERMTS will improve the reliability, safety, reduce the maintenance cost and increase the capacity of the railways and overall improve the sustainability of HSR.

Implementing the preventive maintenance regime on the HSR network will increase the punctuality of trains and will prevent unexpected breakdowns to a minimum. Germany, the Netherlands, and France have already implemented computer models that make track maintenance decisions more efficient. Using the modern rolling stock equipped with advanced technologies that have high performances and offer the high level of comfort for passengers is another way to improve the reliability of travel. Japan changed its rolling stock every 15-20 years.

To improve the reliability of HSR services and reduce the number of accidents it is important to implement for staff a culture of continuous technical learning with broad training that includes the study of possible failures. The analysis of performance of the HSR systems suggests that improving reliability of HSR it will improve safety, increase demand, and increase capacity of rail and overall improve the sustainability of HSR.

5.3.3 External costs affecting sustainability of transport systems

5.3.3.1 Introduction

To make transport systems sustainable there is a need to balance the benefit that transport contributes to society and the negative impact caused by transport on the environment, climate change and health of people. These negative impacts of transport do not include the price that is paid by transport users.

Users do not pay for air and noise pollution or climate change, and they only partially pay for accidents through insurance and congestion through a decrease in productivity. Travel by train brings benefits to those using the transport system, but non-users suffer from the consequence that is caused by using the transport system. In 2008, the total external costs for transport (for EU27) was between 5% and 6% of the total Gross Domestic Product (GDP). Average external costs for road transport (excluding congestion) are over four times higher than external costs for railways whilst for freight services it is over six times higher (Cer.be., 2019). An external cost is one of the major factors that affect the sustainability of transport modes, and most time, it is much higher than the benefit of transportation. It is important to find out how it was generated and possible ways to reduce it.

5.3.3.2 Components of external costs

The most important parts of external costs are congestion, accidents, noise, air pollution and climate change. In 2008, the total external costs from transport in the EU27 (excluding Malta and Cyprus but including Norway and Switzerland) were estimated at €510 billion, excluding congestion (Cer.be., 2019). External costs of transport are growing rapidly because of increasing population and mobility.

To reduce the negative impact of transport and to make more efficient use of the infrastructure there is a need to add external costs of transport to fares, so as this will improve the equity between users and non-users of transport and also equity between users of different modes of transportation. At the present time, users do not pay external costs back; society pays it. Users choose the transport mode using a deceptive price. It is needed to adopt external costs and include them into prices that are charged for journeys.

Transport systems depend on fossil fuels, but there are huge differences in carbon dioxide emissions among the three main modes of transport: namely, railways, highways, and airways. Adding external costs of air pollution to travel fares may produce a shift to more environmentally friendly modes of transportation. Shifting the medium distance travel by car and short flights to HSR will sufficiently reduce the external costs that road and air travel produce. For example, a passenger train powered by electricity produces only 56g of carbon dioxide emissions per passenger-kilometre, short air flight 180g and petrol cars 110g per passenger-kilometre (Thenbs.com., 2019).

In the EU, noise-related external costs will be around €20 billion by 2050. Accident related external costs will be around €60 billion per annum by 2050. The external costs of congestion will be around €200 billion per annum. Only external costs related to air pollution will decrease by approximately 60% by 2050 (Jehanno, 2011).

In the year 2000, in Europe the external cost of road transportation was 84% compared to railways just under 2% (Jehanno, 2011). However, railways in Europe, Asia and the USA have a big variety in their external costs. External costs depend not only on technical characteristics of the transport unit but also on the locations and time of day, but most importantly is the fuel that is being used by vehicles. Figure 5.4 shows the major components of external costs in transportation. Climate Change is responsible for the largest part of external costs (29%).

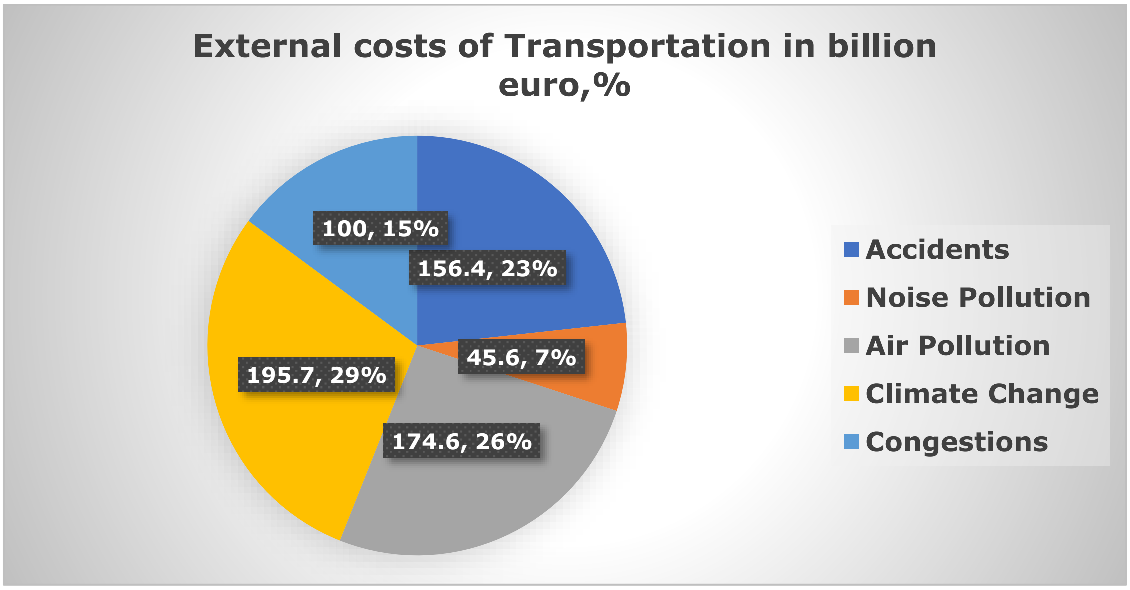

Figure 5.4 External costs of transportation in billion euros, %. (Source: Data taken from various resources)

5.3.3.3 Congestion

Congestion is one of the major external costs of road transport. Although the construction of new roads to relieve congestion might be in some cases validated, it was proved many times that building new roads created more new traffic. The present cost-benefit appraisal process does not calculate the generated traffic and cannot evaluate the environmental costs on the same basis as time savings by monetising them. The cost of congestion in Europe reaches approximately 1% of the total Gross Domestic Product (GDP) annually (Ec.europa.eu., 2019e). Railways also get congested, but this external cost has not been evaluated up to now. The congestion affected some high-speed lines, mostly those that are used by both passenger and freight trains.

To satisfy increasing demand for mobility worldwide, by 2050 there is a need to build around 335000 kilometres of railway track (Dulac, 2013). It was estimated to shift only 2% of traffic from road to rail in the UK there is a need to increase capacity of railways by 25% (Assets.publishing.service.gov.uk., 2019).

The development of the Global Navigation Satellite System for the railway industry and implementation of European Railway Transport Management System (ERMTS) will increase service frequency and as a result will increase capacity of railway systems. Optimising the timetable, using more powerful locomotives, lengthening existing train services, increasing the speed of trains, upgrading infrastructure, electrification of existing lines, and building new lines, these can increase the capacity of railways.

5.3.3.4 Accident costs

One of the largest parts of the total external costs belongs to accident costs, and it is only one of the external costs that have steadily decreased in the past. Road accidents cost $518 billion globally, and it varies for individual countries from 1 to 2% of their annual GDP (Compare Hare, 2019).

The HSR is the safest mode of transportation with fatalities recorded close to zero (Baron, 2009). However, the fatality rates differ in different HSRs. The most outstanding record belongs to Shinkansen HSR in Japan where no accidents have been registered that were followed by fatal injuries to passengers on board since the railway started operating in 1964.

Not all HSRs have good safety records. Recently, there have been a few accidents, and one of them was in February 2016 in Bavaria, Germany. Two commuter trains traveling at a speed of around 100km/h collided on a stretch of single-track that killed 11 people (ITV News, 2016). One of the deadliest train crashes in German modern history was in 1998 when 101 people were killed and

88 more injured (Danger-ahead.railfan.net., 2019). In the last few years, the increasing amount of accidents on HS lines (Spain, China, and France) makes people cautious about the level of safety on HS trains.

Improving the punctuality of railways will improve safety too, as many accidents are caused by trains that are travelling late. Safety records can be improved by improving HSRS and avoiding the use of the level crossings.

5.3.3.5 Climate change

An International Panel on Climate Change predicted that the global temperature would increase from 1º to 6º Celsius from the current level by 2100 (The Independent, 2019). This will depend on future greenhouse gas emissions, and to prevent this change in temperature, there is a need for immediate action to be taken. It was estimated that climate change costs are approximately 1% of world GDP, but by increasing by 2.5° Celsius in temperature it would reduce global GDP by approximately another 1.5% (Maddison & Pearce 1996). The transport industry is the second largest carbon dioxide emissions producer, with 27% after the energy industry, with 34%. The railways contributed just 1.6% of total carbon dioxide emissions produced by the transport industry (UIC, 2008).

The contribution of carbon dioxide by different railway systems differs considerably. This depends on the energy resources that railways use and, on the ways, that electricity for railways is generated. If electricity for HSRs is generated from solid fuels or oil, it will have a higher environmental impact on climate change and higher external costs.

The external costs of climate change for HSR in Germany are much higher than in France. In Germany, about 54% of their electricity is generated from solid fuels compared to France, with only 4.5% of the electricity generated from solid fuels. In France, 85.8% of their electricity is generated by nuclear power stations. For this reason, HSR in France have lower external costs related to climate change, but they have other environmental problems related to storage of waste from nuclear power stations (European Commission, 2010).

Japan generates only 1% of electricity from nuclear power stations and around 30% from solid fuels and 43% from gas. HSR in Sweden uses only renewable energy resources such as hydropower and solar power. Approximately 80% of the railways in Europe and 100% of HSR is powered by electricity, this means that the operation of HSR does not contribute to greenhouse gas emissions.

HS train produces 17g carbon dioxide emissions per passenger kilometre compared to a private car with 115g carbon dioxide emissions per passenger kilometre or to an aeroplane with 153g carbon dioxide emissions per passenger kilometre (European Commission, 2010). However, there is a need for more detailed analyses of secondary carbon dioxide pollution from HSR to fully estimate external costs of climate change related to HSR.

There are many ways to make railways more energy efficient, some of them are: make trains lighter, reduce the axle load, and upgrade the infrastructure. Implementing the regenerative braking system on passenger trains can give up to a 20% reduction in energy use. “Eco Mode” is a computer-based Train Control System that improves techniques of train drivers and as a result reduces the amount of used energy (Kampman et al., 2009). Railways in Europe by 2050 have an ambitious target to have zero carbon dioxide emissions.

5.3.3.6 Noise pollution

Noise levels are continually increasing, and this disrupts sleep, negatively affects health, and reduces property prices. Noise is one of the most important environmental emissions for people who are living next to railways. The financial cost of noise and vibration is significant. It was estimated that noise and vibration pollution vary from 0.06% to 1.98% of the country’s GDP (The Royal Society, 1995). Railway traffic has the lowest percentage of noise pollution compared to air or road. However, not all HSRs have the same level of external costs caused by noise pollution.

ICE3, the HS train in Germany, has the lowest noise level compared to TGV in France, Shinkansen in Japan, or Amtrak trains in the USA. Only TR07, Maglev train of Germany, has a lower noise level than ICE3. The external cost of noise pollution from HSR depends not only on technical issues but also depends heavily on the density of population living next to HS rail lines.

For this reason, external cost of ICE3 in Germany, is higher than external costs of TGV in France, as Germany has a higher density of population and more people are affected by noise from HSR. The public were very concerned about increasing noise pollution from transport, and this was one reason for Shinkansen, HSR in Japan to decide not to increase the speed of HS trains to a higher speed.

There are many ways to decrease the noise emissions produced by railways. One of them is to build the HS line in the cut-and-cover tunnels. Building noise barriers, improving the RS design, and track design will substantially reduce noise pollution from HSRs.

5.3.3.7 Conclusions

There are many ways to make transport systems more sustainable, and this can be made possible through a technological improvement or reducing transport demand, or through a combination of both. Many countries around the world are planning to build HSR, and it is important to look at ways to make them more sustainable. Comparing and evaluating existing roads and looking at the key influencing factors of sustainable railway systems show the way for more sustainable HSRs. One way to have more sustainable transport systems is to reduce the external cost of them. In some cases, it can be more profitable to look at alternative ways to improve transport mobility. It can be upgrading the conventional rail, using tilting trains or looking for a new way of transportation.

5.3.4 Profitability of HSR

The cost of constructing new HS lines is becoming very expensive. A recent study by the European Commission doubt the benefits that is created by the development of HSR. The Eurasian Customs Union (ECU) studied ten transport projects and suggested that the additional economic growth that would be generated by the new transport infrastructure would be much less than originally forecast (Hoyle & Knowles, 1998).

The major factors that affect the performance of HSR are the country's poor general economic performance, the unwillingness to pay higher prices for increased speed, low density of population and competition from the air transport industry. Figure 5.5 shows the estimated cost per kilometre of HSR construction in selected countries.

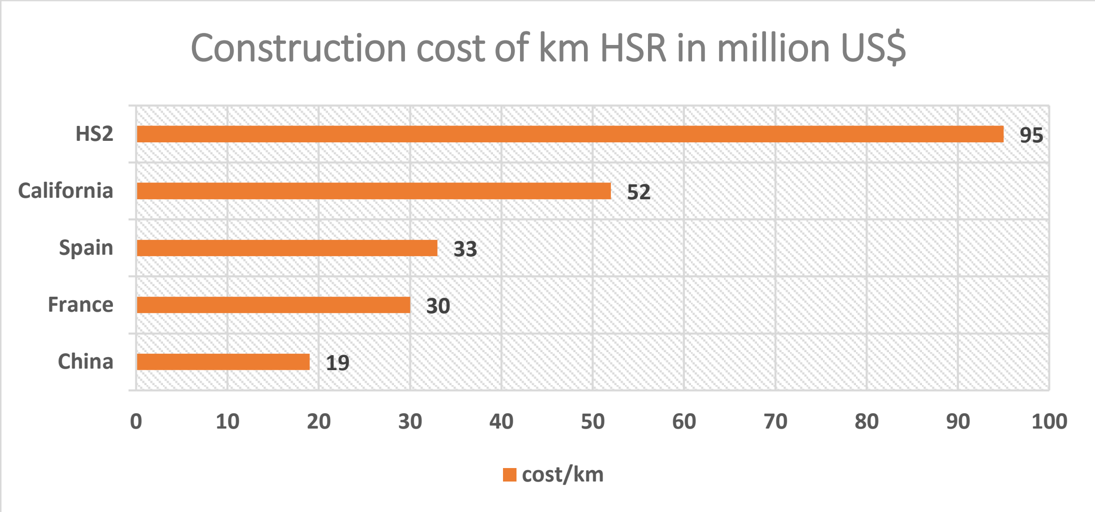

Figure 5.5 Approximated estimated costs per kilometre of HSR construction (Source: Amended from Openknowledge.worldbank.org., 2019)

The highest estimated cost is the HSR in the UK at US$90-100 million per kilometre. The construction of HSR is twice as expensive as up-grade construction and about one half to one-third the cost of tunnel construction. HSR is the most efficient where it is needed to transport thousands of people on distances between 150 and 700km. Corridors that are shorter can be well served with conventional rail, but longer corridors cannot compete effectively with air transport. HSRs are capital intensive, and they are most viable where they are intensively used.

Applying some technical and operational developments such as, track realignment, signalling improvements, tilting trains, increase the number of multi-unit trains, double deck trains can be much cheaper than building new HSR. Investments in upgrading and improving railways can significantly improve capacity, frequency, comfort, and speed. Railway up-grading is more cost effective than new build and has an excellent economic benefit when compared to building new railways.

The most important factors that affect the success of HSR is the technology to be employed and the type of operation. The cost of construction, service, and performance of HSR depends on how straight and flat a track alignment is. Often the less costly is to go around a natural or manmade obstruction than to go over, under or through it. The major categories of cost for new HSR systems are land acquisition, earthwork, structures (bridges, viaducts, and tunnels), systems and rolling stock. Figure 5.6 shows the train passes through residential building in China.

Figure 5.6 Train passes through residential building (Source: Metro.co.uk, 2019)

The development of new railway infrastructure most time overrun preliminary costs by 50-100% in real terms. Inaccuracy in cost forecast is on average 45% for rail, 34% for bridges and tunnels (Nunen et al., 2011). Costs of HSRs increase with increasing design speed. Most transport services in Europe, especially those that need to modernize or expand, show huge losses. Sometimes, revenue is barely enough to cover operational costs. The ridership fees and other user charges on HSR will not be enough to finance the full cost of development. HSRs rarely meet the forecast revenue and many lines have been seeking additional government funding.

The profitability of the new build HSR depends on land value policies and the level of noise mitigation. Land purchase and compensation payments are around 5% of the total construction cost. The construction costs include infrastructure-route preparation, earthworks, civil engineering, type of signalling and power supply.

RS takes a huge part of railway expenditure. To reduce the unit cost in RS production a need to take actions for standardisation in RS manufacturing.

Eurostar travelling from London to Brussels run through three different countries with different power supply and different signalling systems, and for this reason they have been fitted with about 20 different detectors.

All this adds to the cost and complexity of the product and reduces profitability. National railway systems are poorly interconnected with each other, as they have different technical standards and signalling systems. Slow progress towards the standardization of infrastructure, common standards, rules, and regulations means that, for many years to come, international trains will continue to be expensive and complicated (Feilden et al., 1995).

Society continues to fund HSRs. Public transport systems provide important economic and social benefits. HSR provides many opportunities for society. Travellers will benefit from time saving, safety, and high-quality services. Non-users will benefit from reductions in congestions, improved air quality and increasing the safety on roads. An investment in HSR attract more passengers, more people will travel by rail if railways can offer a good value for money journey, time saving, safety, good environment, and a high standard of service. One of the strongest arguments in the development of HSR is the long-term benefit for local communities, but this effect is difficult to predict. In most cases, HSRs can never pay back the investment. However, the developing HSR will improve the accessibility, which in its turn, will expand the labour market and bring the talented workers within easy reach to nearby Centre's. The development of HSR will expand the job market, it increases the distance that labour can travel for a job.

5.3.5 Conclusions

The economic sustainability of transport systems depends on the ability of an economy to grow indefinitely by using available resources in the most productive way. In this research, several relevant papers have been analysed that covered external costs, safety rates, punctuality, and profitability. A high percentage of accidents are caused by trains running late. Improving the reliability of railway services will improve safety and will lead to higher levels of passenger satisfaction, and as a result will lead to an increase in HSR revenues. Several variables have been identified that will be considered for further analyses. These variables are represented in Table 5.13.

Table 5.13 Variables related to economic sustainability of HSR that will be considered for further analysis

Revenue-earning HS traffic-total number of passengers
Length of HSR lines
Average time in vehicle
Average distance travelling per passenger
Level of productivity of HSR
Overall technical efficiency

5.4 Social sustainability

5.4.1 Introduction

Social sustainability means creating more jobs, supporting welfare, and providing a safe and healthy living environment for current and future generations (Nunen et al., 2011). Efficient transport systems can support an increase in employment, redevelop deteriorated areas and improve the well-being of society. Railway transport is becoming an important mode of transportation, as it offers many advantages and role of railway transport in future will increase. The most developed HSR systems belong to Japan, France, Germany, Spain, Italy, and China.

HSR comes with huge costs and therefore it is important to evaluate the benefit that HSR can bring. Examples from around the world show that major cities such as Barcelona, London and Paris have most of the benefit generated by the development of HSR, but periphery regions have much less benefit (Baron, 2009; Dutzik, 2010). Sometimes, transport investments contribute to increasing social disproportion between regions. It was found that the social benefit that is created by implementing HSR depends on the attitude of local authorities (Stanke, 2009). Only implementing the HSR systems would not work effectively as a buster for local economy. The effect of implementing HSR on peripheral regions is difficult to predict, and it is uncertain. Figure 5.7 shows the major factors that can affect the social sustainability of society.

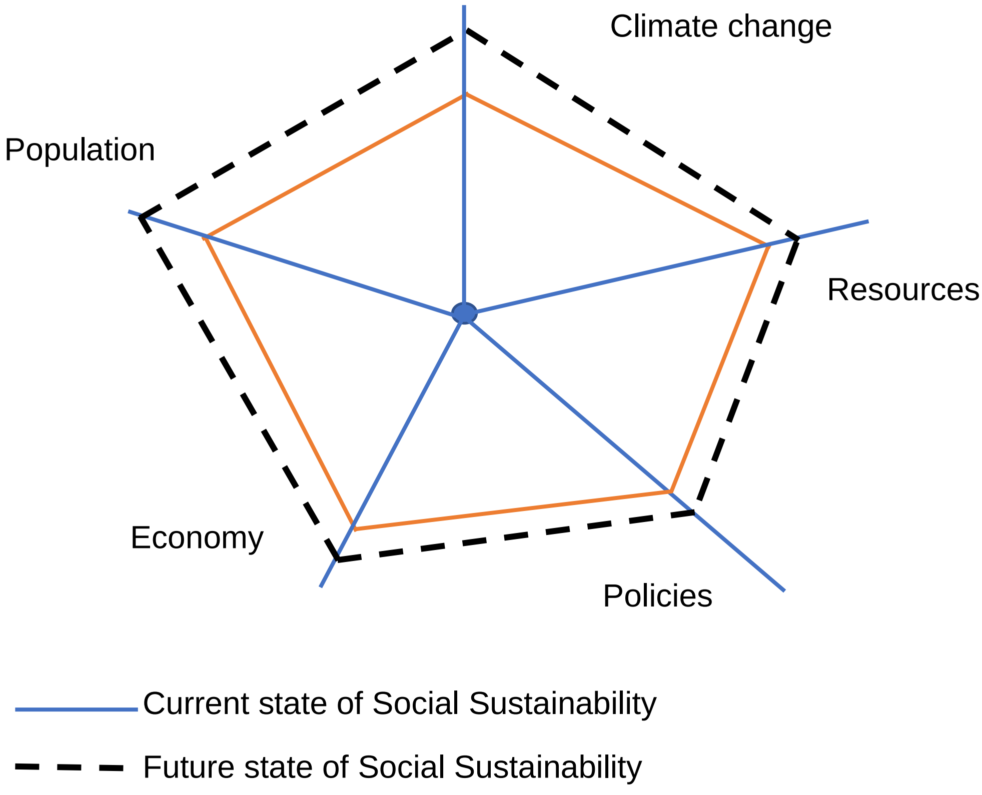

Figure 5.7 Pentagram of social sustainability and related factors

5.4.2 HSR contributes to local development

One of the strongest arguments in the development of HSR is the long-term benefit that HSR brings for local communities, but this effect is difficult to predict. In most cases, HSR can never pay back the investment (Muldowney, 2016). Different infrastructures that have connections with HSR will benefit too, such as airports, larger universities, and tourism areas. Cities such as Lyon and Lille in France have had a large benefit from developing HSR systems.

In 1976, the French government allocated funding for the first HSR, and with the start of building HSR in Lyon, the city flourished. The population of Lyon in 1982 was 1,049,488 (Stanke, 2009), but Lyon is now the second largest metropolitan area in France after Paris. The population of Lyon, after opening HSR services, started to increase, and these changes can be partially linked to the improvement in public transport. The district became a hub that connects international railways combined with public transport and tram stations from which passengers can get to the airport. One reason for the success of re-developing Lyon was the good connection of the centres of economic activities with local transport networks.

The area around the HSR station was re-developed into new business centres after the metro services were extended to the station. In 2015, the population of the metropolitan area of Lyon was 2,214,068 (About-france.com., 2019). It has more than doubled since 1982, although the population of France increased by approximately 16% for that period. Land value in the area surrounding HSR stations in Lyon grew and between 1983 and 1990 the demand for office space increased by 5.2% per year (Stanke, 2009).

After the completion of the HSR link to Paris approximately 6000 new jobs near the station were created and the amount of office spaces near railway stations increased by 43% (Batterbury, 2007). Lyon was boosted by attracting businesses from the same region, whilst firms from Lyon used the TGV to expand their businesses to the Paris market, and in reverse many international businesses opened their branches in Lyon.

After starting the development of the HSR, the economy of Lille prospered, and the depressed areas were uplifted. The population of Lille in 1990 was 1,059,268, but by 2015 the population increased to 1,166,452 (About-france.com., 2019). The local government played a crucial part in moving the HSR station to the centre of the city. This decision brought re-development and prosperity to the city. Residents of Lille travel to work in Paris, Brussels, and London whilst Lille has become the bedroom city. Successful HSR stations in Lille serve not only as transportation hubs but also as places where people like to spend their time. Within the area, there has been newly built hotels, a commercial centre, event halls, many offices, and a public park. HSR can benefit communities surrounding the stations by offering new jobs, improving accessibility and mobility for society, and offering places for socialising. Building new stations or re-developing existing stations encourages the economic development of surrounding areas and can transform the city and regions.

HSR can be the catalyst for regeneration. It has been estimated that areas close to HSR stations have higher employability and have around 2.7% GDP growth more than surrounding areas (Shinkansen, no date). Increasing accessibility positively affects the growth of the economy. For example, increasing accessibility by 1% will allow the economy to grow by 0.25% (Whitelegg & Haq, 2003b).

Some industries benefit from the development of HSR more than others. It was found that employment grew more in the retail, wholesaling, and construction industries. The growth is 16-34% higher in these industries in cities with an HSR station (Albalate & Bel, 2012). Table 5.14 shows the difference in annual growth of industries in cities with and without HSR stations.

Table 5.14 Comparison of cities with and without Shinkansen railway stations 10 years before and after the operation of the Shinkansen (Source: Amended from Baron, 2009)

Sector	Annual growth in % before opening Shinkansen		Annual growth in % after opening Shinkansen	
	Cities with a station	Cities without a station	Cities with a station	Cities without a station
Wholesale	12.9%	20.8%	11.6%	8.7%
Retail	10.1%	13.5%	10.0%	8.6%
Industry	13.7%	14.2%	9.5%	7.8%
Construction	13.8%	14.9%	8.0%	6.4%
Average	**12.6%**	**15.9%**	**9.8%**	**7.9%**
Population	2.7%	3.4%	1.9%	1.6%

The concentration of the service industries becomes higher in cities with HSR stations. However, in the areas between the major HSR stations, unemployment was increased whilst the outflow of working forces from areas to cities with HSR stations was also increased. For example, Tokyo and Osaka in Japan have highly concentrated service industries but in towns between them such as Nagayo unemployment increased (Albalate & Bel, 2012).

Between 1980 and 1993, cities with a Shinkansen station in Japan saw a sharp increase of approximately 155% in their municipal receipts, compared with their national average (PwC, 2017). Many cities benefit from HSR, boosting their economy and drawing forward the redevelopment of cities. St. Pancras station in London was the catalyst for the redevelopment of King's Cross area with major development plans to build 20 new streets, 10 new major public spaces, and up to 2000 new residential units, in addition to cultural venues, hotels and offices (Times, 2016).

It was estimated that bringing HSR to St. Pancras in London brought £10Billion in private investment into the local station area (Stanke, 2009). In Germany, areas surrounding Frankfurt and Cologne HSR stations had a 2.7% increase in economic activity after opening these stations, compared with the rest of the region (Dutzik, 2010). The areas surrounding HSR stations have higher rents for office space than in other parts of the same cities. In Japan, property values near Shinkansen stations are 67% higher than property prices further away (Batterbury, 2007). The cities with HSR stations have higher economic growth than without, but the impact of HSR as a key factor in business location decisions are minor. However, service sector businesses consider this factor when they decide about location.

Retail properties within one-quarter of a mile from railway stations are valued 36.75% higher, offices valued 13.85% higher, residential properties 5.97% higher and industrial properties 7.68% higher (Debrezion et al., 2016). This is put down to the accessibility of public transport. Businesses valued the location of offices near the HSR station if their staff and customers used rail services. It gives an opportunity for businesses to choose staff from a wider labour market to have higher qualified staff. For London, the premium value to property location in a radius of 500m from the railway station is 10.5%, in radius 750m it is 7.6% and in a radius of 1000m is 4.9% compared to property prices located 1500m from a station (Blackmore, 2014).

HSR systems support the urbanisation of major cities by creating new jobs and expanding the market. Such economic benefit which is created by implementing HSR systems very much depends on the attitude of local authorities. Implementing the HSR alone does not work as effectively as it would aggravate with efforts of the local authorities to regenerate depressed areas. The effect for peripheral regions of implementing HSR is difficult to predict, and it is uncertain.

Improving the accessibility and mobility of society supports the growth of the economy, and this typically applies to any transport mode. Development of HSR was considered commercially profitable to major urban cities, of over one million people. However, development of HSR can widen the gap between territorial equity, reduce social cohesion and lead to a polarisation of differences between territories (Monzón et al., 2010). Territories that do not have access to HSR services develop less quickly than territories that have direct access to HSR.

In France, only large cities, such as Lyon, had so benefited from the development of HSR, but in some regions the benefit is less direct. The benefit for medium or small cities with HSR is much lower. Many examples from France and Spain show that transport infrastructure alone does not bring growth with no local government relevant policy to stimulate economic activity (Baron, 2009).

Ashford, UK has had very little benefit from implementing HSR services. With the opening of Ebbsfleet International station, Ashford lost a direct service to Brussels with a reduction of around 50% in services to Paris (Renner et al., 2010). It looks that the larger benefit for the economy of Ashford will be in improving the services to London, as Kent is more strongly linked economically to London than to Paris.

There are three major impacts of HSR on local and regional development. First, HSR can stimulate economic development of a region, changes in land use patterns in the surrounding areas of stations. Second, HSR can change the image of the city as a modern and innovative city. Third, it can create new city districts with hotels, offices, retails, and residential areas. As a result, it increases urbanisation and contributes to the creation of megalopolises with an expanding labour and commercial market (GOV.UK., 2019c).

5.4.3 Developing of HSR will improve employability

It was forecast that the population in Europe will increase to 520.7 million by the year 2035. The European Union has a very ambitious goal to reach 75% employment for the age group between 20 and 64 by 2020. With the threat of a new recession and low GDP growth, the creation of new jobs is crucial for the economy to grow. It was estimated that by 2040 up to 48% of current jobs could be replaced by automation (COMM, 2010). HSR created many direct and indirect jobs. The number of jobs that can be created by the development of HSR could be greater than the loss in other transport sectors through modal shift.

For example, the construction period of HSR from Madrid to Valencia had created over 100,000 direct jobs. During the first five years of service 135,000, new permanent jobs were created. Some studies estimated that for 10 new direct rail jobs, at least 14 new indirect jobs were generated (Jehanno et al., 2011). In California, USA, it was predicted that construction of HSR for the next five years will create 20,000 jobs annually. On the next step, the initial operation sector will have up to 34000 jobs annually. In the next 15 years after finishing the construction of HSR, the number of jobs will increase by 60,000 annually for the following 13 years (Tunneltalk.com., 2019).

HSR provides the opportunity for the creation of indirect jobs as connectivity increases. It also improves the efficiency and competitiveness of the economy. There is also a need to add-on hundreds of thousands of additional jobs in the rolling stock manufacturing industry and new jobs that will be created by the supply chain. According to some publications (Assets.publishing.service.gov.uk., 2019c) the construction of the HS2, its maintenance and the building of new stations will increase the local business activity. In the next five years, there will be 22000 new jobs created in the construction industry and when the line is up and running it will generate around 100000 new jobs.

The total number of employees in the railway sector of Europe in 1991 was 897800 (Kiriazidis, 1994). By 2008 the number of employees on Europe's railways drops to 812,366 (Cer.be., 2019b). There are clear signs that indicate the shrinking of employee forces, which happened for two reasons: first, the decrease in demand for travel by railways and secondly, improved railway technologies and increasing automation of low-skilled jobs. Rolling stock manufacturers have large labour forces. Germany, Spain, Japan, and China are the four major countries that manufacture the RS.

They have significant manufacturing employment. In these countries, at least 500,000 are directly employed in RS manufacturing, and much more indirectly in the supply chain (Renner et al., 2010). In Germany, the direct and indirect jobs that have been created in the manufacturing of RS is almost 200,000, but with rail construction and operations, employment in rail transport rises to 580,000 (Tendersinfo.com., 2019).

HSR not only creates jobs in the railway industry but supports the creating of new jobs in areas where they are implemented (Angeles et al., 2014). The three districts in the centre of Barcelona: Eixample, Sants-Montjuic and Les Corts, surrounding the HSR station have on average 78% more employment than rest of country. The four districts in Madrid: Salamanca, Retiro, Chamberí, and Centro surrounding HSR stations have an average of 132% higher employment.

Development of the HSR supports the creation of many thousand jobs in the industry, moreover, it also supports the creation of new jobs around railway stations.

5.4.4 HSR improves accessibility

The transport system is not only about physical movement, but it is also about improving access to goods and services for the population. Access is defined “as the ability to reach desired goods and services and activities” (Cox, 2013). Public transport is inadequate in terms of the requirements of a modern society for mobility and accessibility, but HSR can fill this gap. With the growing population and urbanisation, demand for a more efficient transportation system is inevitable; there is a need for a link to fixed resources and labour forces. There is a long-term need for access to central cities in different countries.

HSR connects territories and improves global accessibility. HSR improves accessibility in terms of time and distance, creates new regions by linking cities together, and cuts the travelling time between them. The low state of accessibility is regarded as a serious barrier for businesses to grow in peripheral regions. Four major components of HSR accessibility are income, population, density of population and job market (Albalate et al., 2012). Greater distance in commuting from home to work gives a wider range of job opportunities and can represent lower housing costs. Better accessibility makes regions more competitive. Building a new HSR will increase capacity on the conventional network for freight, commuter, and regional rail services.

In Spain, 40% of the population in 2009 had an HSR station within a 50-km radius, but in 2012 this percent increased to 55%, and by 2030 90% of the population will live in a radius within 50km of a high-speed railway station (Jehanno et al., 2011). HSR gives opportunities for people to move away from mega cities to urban areas to benefit from a better quality of the environment and cheaper property prices, but still have the possibility to carry on working in cities. Rural areas in countries with developed HSR are getting close to centres of politics and finance.

In France, HSR transformed depressed industrial areas into prosperous places with booming economies. Implementing HSR was a huge success in improving accessibility across urban areas for commuters. Now Paris is only three hours away from the Mediterranean, less than two and half hours away from London and just over one hour from Brussels. It will significantly improve connectivity with Spain by introducing new lines. Developing HSR brings improvement in local transport systems too. In France from the 20 tram/light-rail systems that were introduced in the last ten years outside of Paris, 18 were built in cities with HSR system (Stanke, 2009).

Around 20% of the UK population live within a 15-minute walk of a local train station, although this figure is different for different areas, in London it can rise to 50%, and only 6% in rural areas (Lucas, 2000). The creation of the HSR network is an important part of the EU policy designed to increase accessibility within the EU, meets the increased demand for transport. However, very often the cost of developing a new HSR was underestimated, but final benefits overestimated (Watson et al., 2019).

In China, HSR reshaped inter-city accessibility that dramatically affected the economic productivity of the country. One example is in the coastal region of Guangdong, China, where reducing the distance by half leads to an average of a 10% increase in business productivity (World Bank, 2018). Improvement in accessibility will expand the labour market area, improve job matching, and eases business-to-business interaction. It can also increase domestic and international trade, as transport improvements can allow businesses to trade over a wider area and provide consumers with more choices (Gov.uk., 2019c). Economic development will grow, and the quality of life will increase.

By improving access to mobility, the HSR contributes to improvement in recreation and tourism, provides the safe and comfortable transportation, creates jobs, and overall generates a new lifestyle. HSR connects cities in large business conglomerate areas. It helps balance living standards and wages across all regions. Accessibility is necessary, but it is an insufficient condition to economic development, as there is a need for a strong government policy to regenerate deprived areas.

5.4.5 HSR offer new opportunities for the tourism and leisure industry

The economic growth, increases in people income, living a longer life, more leisure-time and increased activities all add to the growth in travel. People have a great need for mobility and recreation, and this will lead to traffic growth. Travel distances increased sharply, and it is still increasing, particularly with the operation of airlines that offer cheap flights. In the twenty-first century, transport provides a huge demand for increasing mobility and reduces the friction of distance. Thus, the world is becoming a smaller place.

The distance travelled by each person on the planet is increasing. The average growth rate of passenger kilometres has been rising by 4.6% each year. Average travel for passengers in developed countries annually is 16,645km compared to 2,627km in developing countries (Whitelee et al., 2003).

There is a change in the relationship between work and leisure in the form of increased meetings such as workshops, conferences, and congresses. Railway transport offers wider opportunities to visit friends and relatives, enjoy the countryside, and travel the world. With more people realising of the environmental issues, air pollution and living in cities there has been an increase in the amount of travel by HSR to the seaside and countryside at weekends and holidays. This can be observed in countries such as Japan and China.

HSR connects tourist attraction spots and creates new types of tourists who travel by train to locations of natural beauty and historical places. To satisfy the demand for long-distance travel, night trains will have a substantial potential to offer different ways of travel. HSR can change the international and domestic tourist travel experience by reducing the time needed for travel and costs.

The countries with the most domestic trips per capita per year are the USA, Finland, and New Zealand (Lou et al., 2011). In 2014, Spain hosted nearly 65 million visitors (Thelocal.es., 2019). In 2014, the Spanish tourist industry contributed approximately 6.5% to the total country’s GDP. HSR substantially improved the accessibility for tourist destinations (Thelocal.es., 2019). In the Alicante Province of Spain, because of the improved AVE connection, the number of tourists increased by 20,000 per year, and it brought approximately €3-4 million into the local budget, but it is still irrelevant in relation to the total cost of the HSR line construction (Ub.edu., 2019). In municipalities of Spain with a new AVE project in 2005-2012, the total number of local visitors after opening the HSR services decreased slightly (Ub.edu., 2019). This can be explained by the global crises in 2007. With the opening of HSR stations in Tokyo and Osaka, there have been significant increases in the tourism industry, from 15 to 25% between 1964 and 1975 (Albalate et al., 2012).

The number of tourists visiting Lille after developing HSR increased dramatically, in 1990 it was 34,000, by 1995 it was 149,000, in 2000 it was 431,000 and by 2003 it increased to 517,000 (Jehanno et al., 2011). However, the HSR has limited influence on the growth of tourism. With the increasing public awareness about climate change, there is a need to shift travel from air to HSR for package holidaymakers to get to their holiday destination. The tourism industry contributes around 5% to global GHG emissions and 75% of that belongs to tourism transport, whilst emissions from aviation in the tourism industry are expected to grow by a factor of 2 to 3 (Alin et al., 2011). With the increasing GDP per capita it increases the length of travel and the number of trips (Peterson, 2011). HSR can be a solution for the current transport problems, as railways offer efficient transportation of passengers and freight, low carbon emissions, low environmental impacts, and positive economic growth.

France, Germany, Italy, Spain, UK, and Turkey are included in the ten most popular countries to visit worldwide and they also have the most developed HSR network in Europe. Germany, Sweden, and the UK have upgraded many thousands of kilometres of a conventional network that can be used by HS trains. In the period 2010 and 2020, Spain planned to build about 10,000km of high-speed lines to make railway more accessible for the public. It will give access to 90% of the population to the HS station within 50km of their home (Ec.europa.eu., 2019a). HS night trains can provide a comfortable way to travel with different choices of seats or beds.

5.4.6 Conclusions

HSR has a positive impact on local development and supports the rebalance of regional economies. Implementation of HSR services gives the new opportunities to regenerate the role and image of railway stations and encourages the neighbouring areas for re-development. The population and employment of cities that have HSR services have a growth rate higher than that in cities without HSR direct services. It expands the labour market, business market and helps create new megalopolises. Development of HSR creates hundreds of thousands of jobs in building railway infrastructure, in rolling stock manufacturing industry, operating, and maintaining HSR, and new jobs that will be created by the supply chain.

HSR benefits go beyond the increasing capacity of railways. It brings huge benefits for industries such as the service industry, retail, and hospitality but consumption of hotel services can decrease with the reduction of overnight stays and that decreases tourists' expenditure. HSR improves accessibility between the city centres but isolates the space between these cities. It provides an opportunity to reduce the regional and local inequality which opens more opportunities for regeneration of deprived regions. However, to promote regional equality and foster regional development, it is not enough to only develop HSR as there is a need for economic investment and support from local and national governments.

Large cities with significant service industries benefit from HSR mostly, but industrial and agricultural areas benefit less or not at all. HSR supports agglomeration, and by improving accessibility, local businesses from peripheries move to major cities and serve remote areas. Improving accessibility is essential for economic development, but often it is not enough as it needs government policies and funding to make projects successful.

There is a difference in the impacts of HSR on large and small cities. If large cities flourish from the development of HSR, small cities do not have such a positive impact. One of the critical factors in the success of developing cities with implementing HSR is the size of the city and its metropolitan area, whilst the other factor is the attitude of local government.

Tourism is growing and benefits society by improving employability, and it is a major source of income for many countries. Tourists using the HSR and reaching new destinations will bring money and boost the businesses at their destinations, this will sufficiently boost the local economy, reduce the CO_2 emissions, and improve the economic sustainability of HSR.

In cities with HSR, interconnectivity has improved and, because of this, improved the accessibility and attractiveness of a city centre. The main findings indicate that HSR can bring benefits to society by contributing to the improvement of employability in society and helps re-balance the economy and brings prosperity to the local communities, but that often depends on policies and financial supports from local and national governments. Investing in railways gives not only environmental benefits but also supports economic growth, climate change mitigation, and social inclusion.

In this research, numerous relevant papers have been analysed that cover the impact of HSR systems on the local community, employment rate, accessibility, and tourism. Major variables that relate to social sustainability of HSR have been identified and will be considered for further analyses. Variables related to social sustainability of HSR is represented in Table 5.15.

Table 5.15 Variables related to social sustainability of HSR that will be considered for further analysis

Surface area of country
Population
Density of population
GDP per capita
Land taking by HSR
Mean annual staff number

5.5 Conclusions

In the last twenty years a serious change in passenger transportation has taken place which are caused by changes in demography, economy, and technology. Every year the distance that people travel increases. As the population grows and urban density increases the demand for a more efficient transport system is necessary. The HSR is a fast-growing mass transportation mode. It can offer high capacity, safety, less energy use and as a result, less pollution. However, the profitability of HSRs heavily depends on the expected volume of demand, but demand depends on the willing-to-pay and density of population. Sustainability, efficiency, reliability, and safety are the main objectives for developing HSR.

The question that motivated this research was: is HSR sustainable? From the evidence that has been gathered from different resources a conclusion is that HSR is not sustainable today, as it uses non-renewable natural resources, cause accidents and fatalities, pollute the environment. The demand for transport will grow and the HSR must be the mode of the future, but it must be more sustainable.

There are many ways to improve sustainability and one is to find relevant variables that influence the performance of HSRs. For this reason, the number of variables that relate to economic, environmental, and social sustainability of HSR has been studied. The selected variables will be analysed in Chapter 7.

Chapter 6

Data Used for Analysis

6.1 Introduction

In defining the variables set to be testing, reference was made to several previous papers that analysed the inputs and outputs to evaluate the rail productivity. The data represents a mix of variables used in relation to capacity, service, and financial measures.

In the literature, it is still not clear which inputs and outputs for DEA are needed to use to analyse the performance of HSRs. This study reviewed past studies to choose outputs and inputs. Also, the consideration was influenced by the availability of reliable data. It was observed that most of the previous studies used a narrow range of data.

6.2 Defining criteria

The decision has been taken to consider, for input, the size of HSRs network and for output, the number of passengers and passenger-km, contextual variables includes the average distance per passenger, electric power consumption, train movements, average time on a train, land taken, the number of staff, population, density and income. Zhou et al. (2007) concluded that the most popular economic input is capital, energy consumption is the most used environmental input and the number of employees and population are commonly used as social input indicators.

Output includes GDP and carbon dioxide emissions. The social outputs include employment, punctuality, and safety. This study focuses only on passenger services. For this research, a set of one input and two outputs measures were chosen based on these criteria. The inputs are length of HSR lines and outputs are the number of passengers and passenger movement. The input factor that is included in this research has an obvious influence on the outputs.

The ten HSRs and eight years of data for these HSRs have been considered in the analysis. It was presumed that there have been no technological changes in the selected HSRs. This was done to avoid significant differences in technical efficiency. The topographical differences and regulatory differences also were not considered. The data drawn from International Railway Statistics published by the International Union of Railways (UIC, 2010-2017). Annual data for 10 HSRs worldwide has been used. They are France, Japan, China, Turkey, Spain, Italy, Germany, Korea, Taiwan, and the Netherlands over the period 2010-2017. The size of the sample has impacts on the results of the DEA and must follow two rules: $n \geq ms$, and $n \geq 3(m+s)$, where n=number of HSR, m=number of inputs and s=number of outputs. In this research, m=1, s=2 and n=10 (Cooper et al.,.2006). The sample size is larger than the desirable size.

Analysing the performance of HSR, the number of non-discretionary variables were collected, such as density of population and GDP. In analysing the productivity of the selected HSRs, the average traction power was taken into consideration. This will help to capture the differences in railway transport technology and how it affects the technological productivity of HSR.

In an analysis of the environmental impact, the value of 5ha land to construct 1km of HSR was adopted from Chen et al. (2015). Also, the HSR productivity depends on travel time savings. This can be drawn from differences in average speed of the HSRs. Majority of the data is obtained from International Railway Statistics published by the International Union of Railways. Table 6.1 shows the selected data, data definition and construction.

Table 6.1 Variables for evaluation of performance efficiency of selected HSRs (Source: Author's creation)

Input/output	Categories	Variables
Input	Capital	Length of HSR line
Output	Service	Trains movements
Output	Service	Passengers movements

For the second stage of research selected 16 variables that can influence the difference in efficiency and productivity of selected HSR and they represented in Table 6.2.

Table 6.2 Variables selected for IBM SPSS analysis

Social	Economic	Environmental
Surface area of country	Revenue-earning HS traffic	Annual electric power consumption
Population	Length of HSR lines	HSR traffic
Density of population	Average time in vehicle	Average traction power of train
GDP per capita	Average distance travelling per passenger	Number of HS train seats
Land taking	Productivity of HSR	Total number of seats
Annual staff number	Overall technical efficiency of HSR	Average number of seats per train

The hypothesis of this research is that high GDP, the high density of population and longer average distance travelling per passenger have a positive relationship with OTE and positively influence the sustainability of the HSRs, but high average traction power, longer passenger time in the vehicle and higher land take have a negative relationship with OTE and negatively affecting the sustainability of HSR. Six variables have been selected that can influence the efficiency and productivity of the selected HSRs and they are represented in Table 6.3.

Table 6.3 Variables that can influence the efficiency of selected HSRs (Source: Author's creation)

Expected Effect	Categories	Variables
Negative	Environmental	Average traction power
Positive	Economical	GDP
Positive	Social	Density of population
Positive	Economical	Average distance travelling per passenger
Negative	Social	Passenger time in vehicle
Negative	Environmental	Land taken

The Capital Variables

The data for fixed asset is the length of HSR lines with a maximum line speed >=250kph, measured in kilometres. Most of the data was taken from UIC Statistics, 2010-2017.

The Economic Variables

GDP for selected countries for the period 2010-2017 are taken from the World Bank website and it is presented in constant US$ 2010. The average distance travelling per passenger is represented in km and taken from the UIC website.

The Social Variables

The population density for the 2010-2017 period taken from the World Bank website. Passenger time in vehicle was calculated dividing average distance travelling per passenger by average speed of High-Speed trains in selected countries and represented in km per hour. The average speed of HSRs was calculated taking time and distance from the timetables of the selected HSRs.

The Environmental Variables

Land is a finite natural resource and how it is used can be one indicator of environmental sustainability. The land taken by HSR is calculated based on 5ha per one km HSR. The value of 5 ha of land per one km was used in the previous studies by (Chen et al., 2015). The average traction power in kW was calculated for 2017 using data from UIC websites. Train movements are the passenger train movements of the operator in thousand train-km from Railisa UIC Statistics.

The provided service variables

The train movements are the passenger train movements of the operator in thousand train-km from Railisa UIC Statistics. Passenger movements are the revenue-earning HS traffic calculated in millions of passenger-kilometres. Data taken from Railisa UIC Statistics.

6.3 Data sets

The tables below summarize the data set for inputs and outputs of 10 HSRs for the period 2010-2017. The full data sets are represented in Appendix A.

Table 6.4 GDP per capita in selected countries 2010-2017 (in US$ 2010) (Source: Data worldbank., 2019 & countryeconomy., 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	22086	22724	23123	23685	24323	24870	25484	26152
Spain	30736	30321	29414	29008	29496	30532	31505	32405
Germany	41785	44125	44259	44354	45022	45412	45923	46747
Turkey	10672	11683	12052	12866	13312	13898	14117	14936
Taiwan	19262	20912	21270	21888	22639	22374	22541	24292
The Netherlands	50338	50937	50212	49969	50497	51410	52267	53597
France	40638	41283	41158	41183	41374	41642	41968	42567
China	4560	4971	5336	5721	6108	6496	6894	7329
Italy	35849	35994	34885	33887	33615	33968	34313	34877
Japan	44507	44538	45276	46249	46484	47163	47660	48556

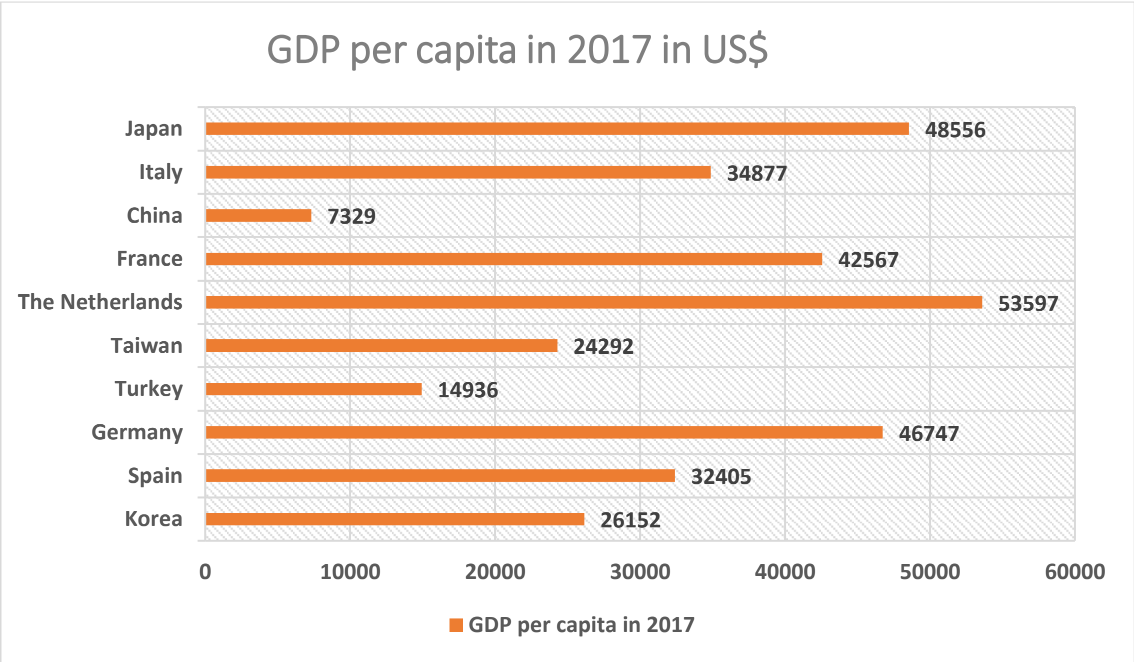

Figure 6.1 GDP per capita in the selected countries in 2017 (Source: Data.worldbank., 2019; countryeconomy., 2019)

Table 6.5 Average distance and time travel per passenger in the selected countries in 2017 (Source: Calculated by Author)

Country	**Operator**	**Average distance travelling per passenger in 2017 in km**	**Average operational train speed in km/h**	**Average passenger time in vehicle in h**
Korea	Korail	249	154	1.61
Spain	Renfe	386	202	1.91
Germany	DB AG	328	168	1.95
Turkey	TCDD	317	149	2.12
Taiwan	THSRC	183	152	1.20
The Nederland	Intercity	100	130	0.76
France	SNCF	464	243	1.90
China	CR	380	282	1.35
Italy	FS	322	191	1.69
Japan	JR	233	203	1.14

Table 6.6 High-Speed Lines in the selected countries with line speed 250 kph and over (there are some exceptions) in km (Source: Uic-stats., 2019; Uicorg.,2019c)

Country	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Korea	369	369	369	369	369	596	657	887
Spain	1684	1759	1809	1919	1908	1908	2503	2852
Germany	864	864	864	881	881	880	994	1658
Turkey	232	444	444	444	632	724	724	724
Taiwan	345	345	355	345	345	345	350	354
The Netherlands	n/a	n/a	n/a	n/a	n/a	n/a	n/a	120
France	1848	1857	1857	1857	1857	2043	2166	2814
China	4675	6095	8442	10437	n/a	18752	20305	26869
Italy	685	652	652	675	856	856	909	896
Japan	2620	2620	2620	2620	2743	n/a	n/a	3041
USA	n/a	n/a	n/a	n/a	n/a	n/a	n/a	735

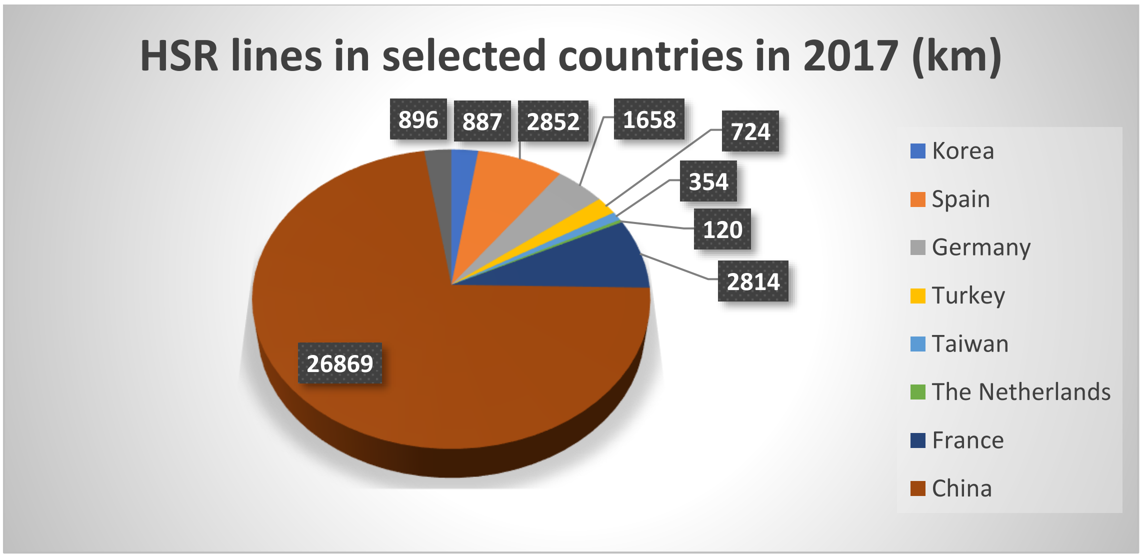

Figure 6.2 Length of HSR lines in the selected countries in 2017 (Source: Uic-stats., 2019; Uicorg.,2019c)

Table 6.7 Density of population in the selected countries (people per km^2 of land area) (Source: Data.worldbank.,2019b; countryeconomy., 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	509	513	515	517	520	523	525	527
Spain	93	93	93	93	92	92	93	93
Germany	234	230	230	231	232	234	235	236
Turkey	93	95	96	98	100	101	103	104
Taiwan	644	645	648	650	651	653	654	655
The Netherlands	492	495	496	498	500	502	505	508
France	118	119	119	120	121	121	122	122
China	142	143	143	144	145	146	146	147
Italy	201	206	202	204	206	206	206	205
Japan	351	350	350	349	349	348	348	347
USA	33	34	34	34	34	35	35	35

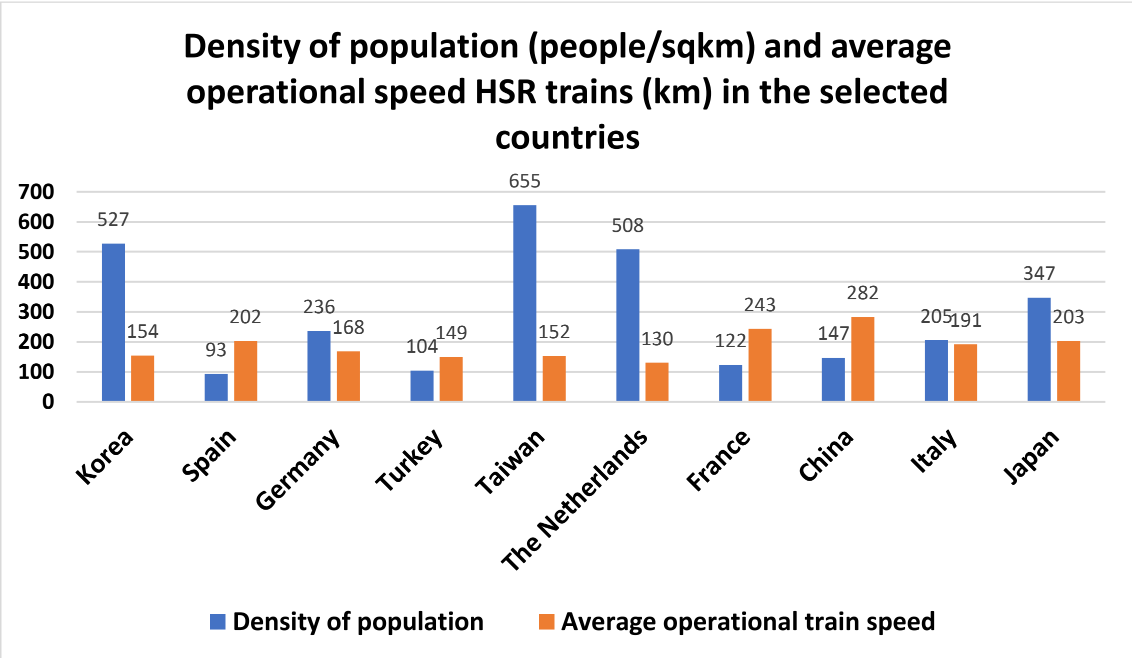

Figure 6.3 Combined density of population and operational speed of HSR trains in the selected countries in 2017 (Source: Data.worldbank.,2019b; countryeconomy., 2019)

Table 6.8 Railway operators

Country	Abbreviation used by the United Nations	National Railway Operator	Abbreviation for National Railway Operator
South Korea	KR	Korea Railroad Public Corporation	Korail
Spain	ES	Spanish State-owned Enterprise	Renfe
Germany	DE	Deutsche Bahn AG German Private Railway Company	DB AG
Turkey	TR	State Railways of the Republic of Turkey, National Railway Company	TCDD
Taiwan	TW	Taiwan High Speed Rail Corporation, Private Company	THSRC
The Netherlands	NL	Nederlandse Spoorwegen, Railway State-owned Company	NS
France	FR	The Societe Nationale des Chemins de Fer, France National State-owned Railway Company	SNCF
People's Republic of China	CH	China Railway Corporation, State-owned Enterprise	CR
Italy	IT	Ferrovie dello Stato Italiane S.p.A., Railway State-owned Enterprise	FS
Japan	JP	Japan Railway Group, seven For-profit railway companies	JR

6.4 Conclusions

Most of the data is drawn directly from UIC statistic websites and used in research for the period 2010-2017. The data can be classified as reliable. In the exception of two cases: it was a lack of data for the USA HSR and for NL HSR, where there was found to be some abnormalities. Some data for specific periods were missing and, in this case, the average statistics was used.

Chapter 7

Factors affecting sustainability of HSR

7.1 Introduction

In this research, the DEA Malmquist production index model has been employed. The main objective of using DEA is to find the best performing HSR among the selected HSRs. The major task of using the DEA method is to look for ways to maximise HSR productivity in producing the maximum outputs by using available inputs. The data source is not 100 percent accurate as some data is missing and averages have been taken for calculation, which can affect the results of DEA model calculation. As a result of this, only the range can be found. To analyse the factors that can affect productivity and efficiency of selected HSRs, the IBM SPSS software was applied. Figure 7.1 shows the flowchart of the selected variables analysis.

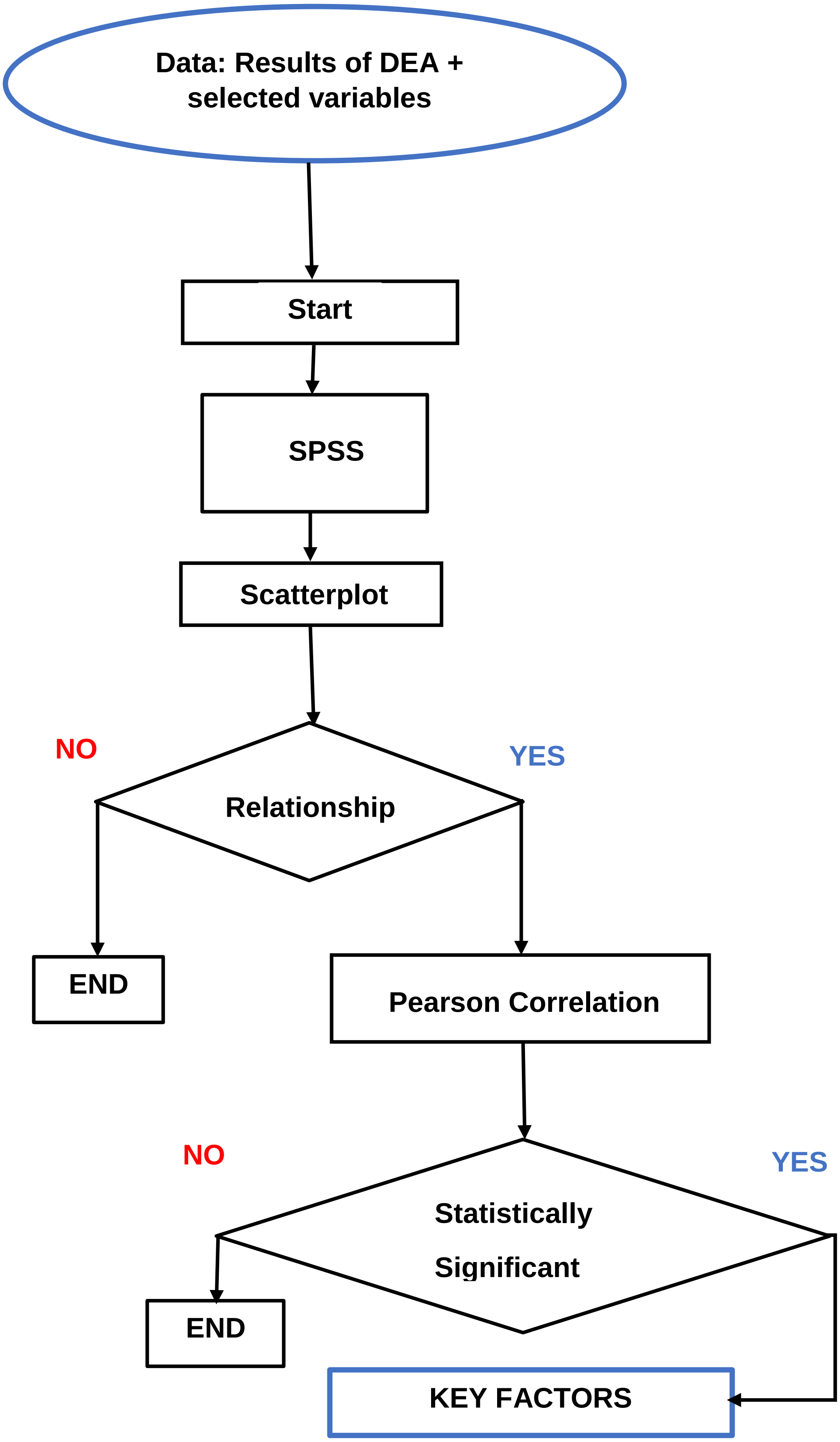

Figure 7.1 Flowchart of the selected variables analysis

7.2 Extracts from DEA simulation

7.2.1 Descriptive statistics

Table 7.1 shows the descriptive statistics of variables (averaged for ten HSR systems) that have been selected for DEA simulation.

Table 7.1 Descriptive statistics, the extract from DEA simulation

Variables	Mean	Std. Dev.	Min	Max
Number of passen. (k-pass)	230402.7	464939.27	4098	1517800
HSR traffic (Mpass/km)	82288.2	176756.03	413	577635
Average travel distance per Passenger (km)	296.2	106.92	100	464
Number of Operational Staff (Full Time Equivalent)	255223.5	565073.49	3222	1841500
HSR length (km)	4021.5	8100.21	120	26869
Train mov. (ktrain-km)	271035.9	254675.92	17294	785420
Power consumption (Giga Watt per hour)	3209.9	2911.53	0	7969
Density of population	294.4	203.36	93	655
GDP per capita ($USA 2010)	33146.8	15124.44	7329	53597
Average time per Passenger on train (h)	1.56	0.44	0.76	2.12
Land taking (ha)	20107.5	40501.07	600	134345

In Table 7.1, a big difference was observed in the value of variables. The smallest HSR network belongs to the Netherlands and the largest to China, which will increase to 30000 km by 2020 (The Economic Times, 2019).

7.2.2 Summary of CRS MI DEA output-oriented model

Technical efficiency or managerial efficiency represents the success of an HSR to convert inputs to outputs and operate at the right return to scale.

Efficiency= Σ of weight outputs of HSR under assessment /Σ of weight inputs of the unit under assessment

Technical Efficiency Changes (TEC) shows the changes in the distance of an observed HSR from the efficient boundary. The output-oriented DEA model maximise outputs for given inputs, which is presented by the formula below:

Maximise $h_0 = \sum_{r=1}^{p} UrYr / \sum_{i=1}^{m} ViXi$, (1)

Subject to: $\sum_{r=1}^{p} UrYr / \sum_{i=1}^{m} ViXi \leq 1$ (2)

Where Yr refers to the p outputs produced and each of them is weighted at Ur; using m inputs Xi, each of them is weighted at Vi. Where the weight defines the relative importance of each inputs and outputs in the efficiency calculation (Pidd, M., 2005).

Productivity represents the ratio of the actual productivity with the best performer (Emrouznejad et al., 2011) and tells how well HSR operates compared to the best performer. Productivity Boundary Change over 1 means that productivity of HSR has risen and increased outputs, less than 1 it means that HSR has fallen in productivity and the output decreases. If BC is equal 1, HSR shows stable productivity. The BC shows the shift in the Most Productive Scale Size of the mix of inputs and outputs of the HSR.

There is a possibility to measure productivity change by Malmquist Indices. A value over 1 implies improvements, a value less than 1 implies deterioration and a value equal to 1 implies stability (Juo et al., 2013). Maximum productivity is if there is no more possibility to increase output with the same input or to produce the same output with less input (Emrouznejad et al., 2011). In this research, the data provided for ten HSRs over the period 2010-2017. The traditional Malmquist Index does not offer circular productivity changes. The Circular Malmquist Index shows the changes of productivity from period 2010 to 2011, 2011 to 2012, 2012 to 2013, 2013 to 2014, 2014 to 2015, 2015 to 2016 and 2016 to 2017, it can also be calculated the changes from period 2010 to 2017. CMI measures the total productivity changes between two-time periods by calculating the ratio of distances of each DMU in each period comparative to a general technology

(Emrouznejad et al., 2011). The summary of CRS MI DEA simulation is represented in Table 7.2.

Table 7.2 Summary of CRS MI DEA simulation (Source: Extract from DEA simulation)

Name	Model 1							
Orientation	Output Oriented							
Return to Scale	CRS							
MPSS & Ident. RTS	Disabled							
Super Efficiency	Disabled							
Malmquist Index	Circular Malmquist Index							
Bootstrapping	Disabled							
Input Variables	(I) HSR line							
Output Variables	(O) HSR traffic	(O) Train movements						
Selected Periods	2010	2011	2012	2013	2014	2015	2016	2017
DMU Selections								
	Selection 1	10 DMU(s)						
Categorical Selections	NO							
Weight Restrictions	Disabled							

Table 7.3 shows the results of the CRS MI DEA simulation for period 2016-2017. The results for the period 2010-2017 of CRS MI DEA simulation are shown in Appendix B.

Table 7.3 Results of CRS MI DEA simulation for the period 2016-2017 (Source: Extract from DEA simulation)

	Period:	2016 to 2017	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	1.21	0.68	1.79	75.2	50.83	
ES	0.16	0.92	0.18	17.85	16.35	
DE	0.69	0.64	1.08	81.2	51.59	
TR	0.13	1.2	0.11	7.67	9.19	
TW	2.74	1	2.74	100	100	
NL	0.23	1.1	0.21	18.08	19.96	
FR	0.83	0.84	0.99	74.13	62.16	
CH	0.94	0.95	0.99	67.8	64.52	
IT	1.01	1.03	0.99	42.41	43.53	
JP	0.99	1	0.99	100	100	

Where:

CMI -Circular Malmquist Index (or Malmquist Productivity Index),

EC- Technical (Managerial) Efficiency Catch Up,

BS- Boundary Shift (Technological Efficiency Change).

CMI decomposed into different sources of EC and BS growth (Emrouznejad et al., 2011). The technical efficiency change computes the changes in using available technology and represented by an HSR movement along the production frontiers. Technical efficiency can be responsible for travel demand flexibly by adjusting the supply scale. The technological efficiency change showed the ability of HSR to invest in new technologies, advanced information technology systems, equipment and rolling stock.

7.2.2.1 Annual productivity change for the selected HSRs in the period 2010-2017

Productivity (usage of resources) and efficiency characterise business performance, and it needs to look at ways to improve productivity and efficiency. The productivity of DMU is a ratio of produced outputs to its used inputs (Productivity = Produced Output /Used Input). The productivity represents the effectiveness of used resources to get maximum outcome (Emrouznejad et al., 2011). Table 7.4 shows the Annual Factor Productivity Change.

Table 7.4 Annual Productivity change for the selected HSRs for period 2010-2017 CRS-MI output-oriented approach (Source: Author's Creation)

Period	KR	ES	DE	TR	TW	NL	FR	CH	IT	JP
2010/2011	2.22	0.22	0.96	0.11	1.71	0.19	0.99	1.24	1.14	1.06
2011/2012	2.03	0.20	1.04	0.12	1.56	0.19	0.99	0.99	1.04	1.09
2012/2013	2.00	0.19	1.04	0.16	1.63	0.19	0.99	1.20	0.94	1.00
2013/2014	2.11	0.20	1.01	0.12	1.75	0.13	1.00	0.94	0.81	0.97
2014/2015	1.70	0.22	1.05	0.13	2.28	0.25	0.90	1.06	1.02	1.04
2015/2016	1.68	0.18	1.12	0.13	2.45	0.19	1.02	1.11	0.94	0.98
2016/2017	1.21	0.16	0.69	0.13	2.74	0.23	0.83	0.94	1.01	0.99

Table 7.4 shows that only two HSRs KR and TW have growth in productivity through all periods 2010-2017. The productivity of DE has grown from 2011 to

2016 and dropped in 2017. The productivity of ES, NL and TR through all periods experienced negative growth.

Figure 7.2 shows the productivity change by the selected HSRs in the period 2010-2017.

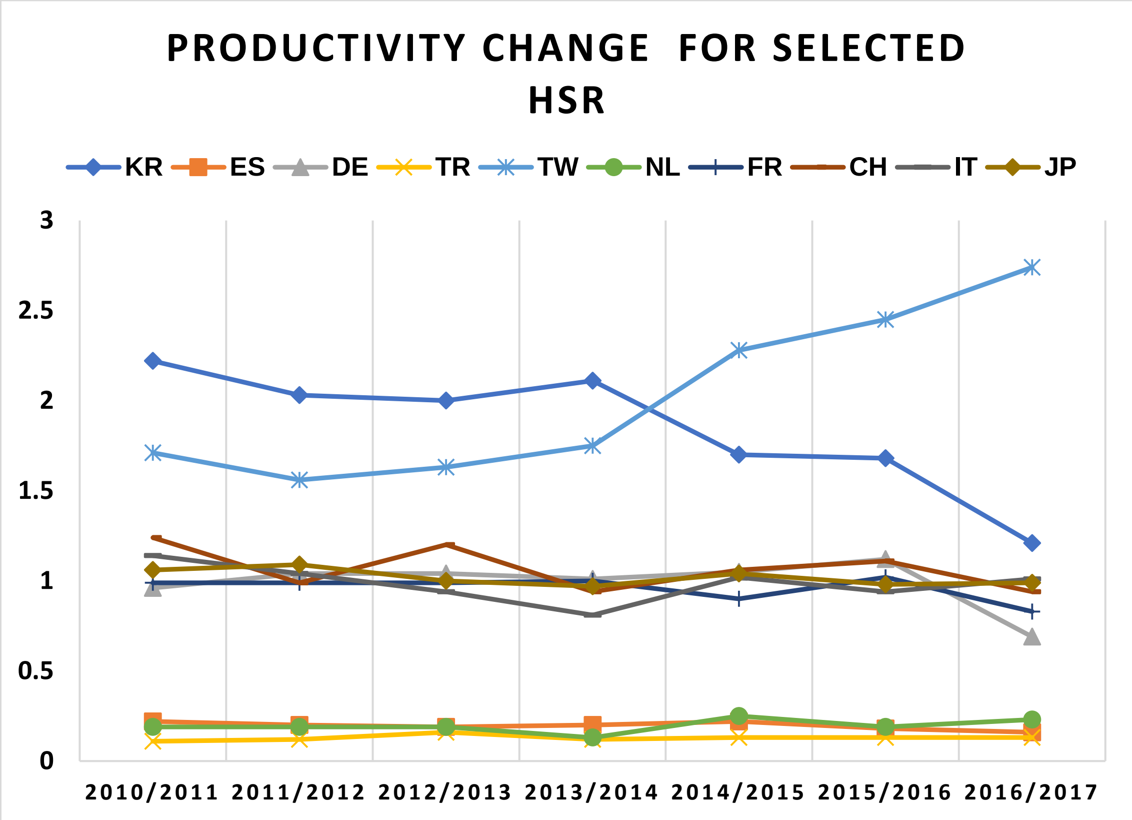

Figure 7.2 Productivity change for the selected HSRs in the period 2010-2017 (Source: Author's creation)

If productivity change equals one, it means that there have been no changes. If productivity is less than one, it means deterioration of productivity. Figure 7.2 shows that there can be three groups of HSRs observed. The first group (ES, TR, NL) has a negative growth in productivity, the second group (FR, CH, IT, JP, DE) productivity growth fluctuating around 1 and the third group (KR, TW) has productivity growth substantially higher than 1. Only one HSR, TW has a visible increase in productivity, which consistently increases from 2011 to 2017. From 2013, KR HSR has a sharp decrease in productivity. This can be explained by the number of accidents on HSR that affected commuter confidence in safety of HSR which has resulted in the decrease of passengers.

7.2.2.2 Annual technical efficiency change for the selected HSRs in the period 2010-2017

Efficiency is the ratio of the actual input to the standard output that should have been produced and represents the level of resource usage. Efficiency=Actual Input/Defined Standard Output. Technical Efficiency (TE) can be analysed in two ways: input-oriented TE, when focus is on reduction of input to achieve a given output and output-oriented TE where focus is on increasing outputs on a given set of inputs (Emrouznejad et al., 2011). Table 7.5 shows the Technical Efficiency score changes.

Table 7.5 Annual Technical Efficiency change for selected HSRs in the period 2010-2017 CRS-MI output-oriented approach (Source: Author's creation)

Period	KR	ES	DE	TR	TW	NL	FR	CH	IT	JP
2010/2011	1.00	0.74	0.79	0.58	0.93	0.89	0.80	0.87	0.92	0.86
2011/2012	1.00	0.93	1.02	1.28	1.00	1.01	0.96	0.95	1.00	1.04
2012/2013	1.00	1.05	0.97	1.26	1.05	1.05	0.97	1.17	0.92	0.97
2013/2014	1.00	1.01	0.97	0.92	1.08	0.70	1.00	0.94	0.81	1.05
2014/2015	0.75	1.26	1.18	1.18	1.00	1.77	1.02	1.21	1.16	1.09
2015/2016	1.01	0.83	0.97	1.03	1.00	0.75	1.04	1.13	0.96	1.00
2016/2017	0.68	0.92	0.64	1.20	1.00	1.10	0.84	0.95	1.03	1.00

The Technical Efficiency (TE) of HSR shows how well used a railway network is to provide the achieved number of passengers and passenger-km compared to the best performing frontier.

From Table 7.5 it can be seen there are no HSRs efficient through the full period and only one HSR is efficient in the period 2011-2017, TW. All other selected HSR have a fluctuation in Technical Efficiency scores. There are possible opportunities to increase outputs without increasing inputs.

Figure 7.3 shows the Technical Efficiency Change by the selected HSRs in the period 2010-2017.

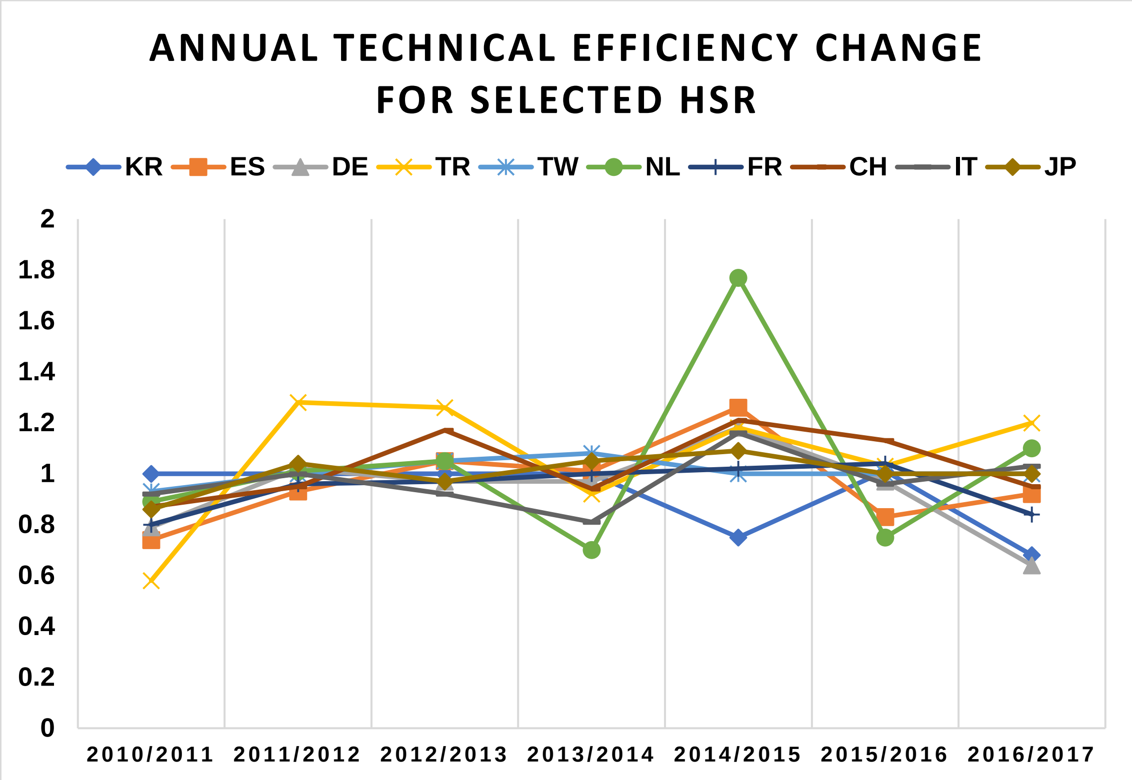

Figure 7.3 Annual technical efficiency change for the selected HSRs in the period 2010-2017 (Source: Author's creation)

Figure 7.3 shows that the changes fluctuated around 1, however, there was a substantial increase in 2011/2012 in technical efficiency change by TR HSR and NL HSR in 2014/2015. For TR HSR, changes in technical efficiency can be explained by a substantial increase in the number of passengers after two years of operation. TR HSR started operation in 2009. For the NL HSR, results look abnormal. For this reason, UIC Statistics have been contacted, and they suggested not to take into consideration results of analysis related to NL HSR as data referring to NL HSR is not reliable. In 2016/2017 five HSRs have negative growth in Annual Technical Efficiency Change and three HSRs have growth and two HSR (TW and JP) the technical efficiency change is equal 1 that means no changes to the previous period.

7.2.2.3 Annual technological change for the selected HSR

The technological efficiency change involves the ability of HSR to invest in new technologies, advanced IT systems and equipment. Table 7.6 shows the Technological Change score for the period 2010-2017.

Table 7.6 Annual Technological Change for the selected HSRs in the period 2010-2017 CRS-MI output-oriented approach (Source: Author's creation)

Period	KR	ES	DE	TR	TW	NL	FR	CH	IT	JP
2010/2011	2.22	0.29	1.22	0.19	1.84	0.22	1.23	1.43	1.23	1.23
2011/2012	2.03	0.21	1.01	0.09	1.56	0.19	1.04	1.04	1.04	1.05
2012/2013	2.00	0.19	1.07	0.12	1.55	0.18	1.03	1.03	1.03	1.03
2013/2014	2.11	0.19	1.04	0.13	1.62	0.18	1.00	1.00	1.00	0.92
2014/2015	2.28	0.18	0.89	0.11	2.28	0.14	0.88	0.88	0.88	0.95
2015/2016	1.66	0.21	1.15	0.12	2.45	0.26	0.98	0.98	0.98	0.98
2016/2017	1.79	0.18	1.08	0.11	2.74	0.21	0.99	0.99	0.99	0.99

Table 7.6 shows that in the case of Technological Change KR and TW HSRs have experienced positive efficiency growth, but ES, TR and NL through all selected periods experienced a negative efficiency, FR, CH and IT HSRs in period 2010-2013 have positive efficiency growth but in period 2014-2017 efficiency decreased. Figure 7.4 shows that there can be three groups of HSRs observed in changes of annual technological efficiency scores.

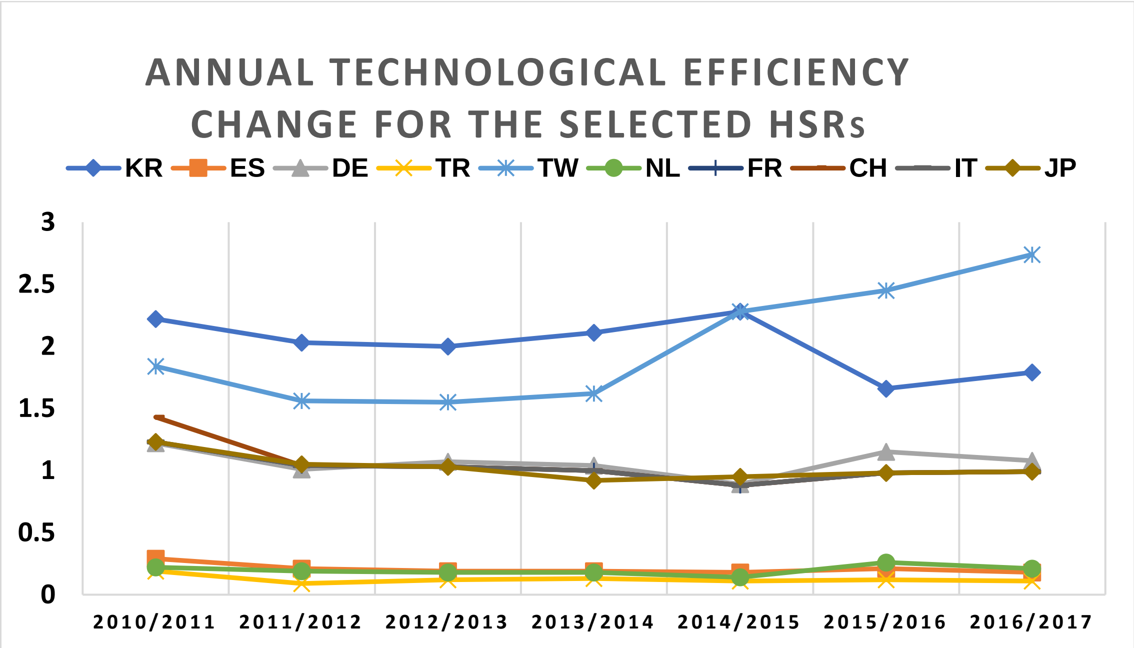

Figure 7.4 Annual technological change for the selected HSRs in the period 2010-2017 (Source: Author's creation)

The first group (ES, TR, NL) shows technological changes in the negative area, the second group (DE, FR, CH) shows the changes fluctuating around 1 and in the third group (KR, TW) changes are observed between 1,5 and 2.74. This can be explained by the fact that KR and TW HSRs went into operation in 2004 and 2007 accordingly. They employ the most advanced technologies, and for this reason they show the highest score in technological efficiency.

7.2.3 Investigation of efficiency trend for the selected HSRs by applying CRS MI DEA output-oriented model

The efficiency of HSRs compared with efficiency levels of other HSRs, but not to ideal conditions. The efficient HSRs are those that attain an efficient frontier and has efficiency score=100%, inefficient HSRs are identified by a rating of less than 100%. The fully efficient HSR is if the efficiency score = 100% and all slack variables are equal to zero. If efficiency score = 100% but some slack variables are positive, the HSR is weakly efficient. The extreme efficient HSRs have an efficiency score greater than 100%. In the case of extreme efficiency of HSRs a Super Efficiency approach can be used (Emrouznejad et al., 2011). This approach allows a ranking of efficient HSR in a similar way to the ranking of inefficient HSRs. It is important to analyse what caused the inefficiency of selected HSRs, managerial underperformance, or inappropriate scale size.

The CRS model assumes that all DMUs operate at an optimal scale (Sufian et al., 2011). There is no significant relationship between the scale of operations and efficiency (Avkiran, 2001). It calculates the overall technical efficiency (OTE) which includes the Scale Efficiency (SE) and Pure Technical Efficiency (PTE). The OTE gives the possibility to define reasons for an inefficiency, this is because of the input/output ratio, or to the scale size (Emrouznejad et al., 2011). The SE gives the ability to decide on the size of the HSR network. The inappropriate size of HSR can be a case of technical inefficiency.

The technical efficiency shows the possibility of HSR to produce maximum output with a given input that is measured by input/output ratio. The OTE in the CRS model gives the same technical efficiency scores whether there is no difference in input or output oriented models. Table 7.7 represents percentage of efficiency of selected HSRs in 2017. Two HSRs in 2017 were efficient TW and JP. The efficiency results for period 2010-2017 of CRS MI DEA simulation is in Appendix B.

Table 7.7 Efficiency scores for the selected HSRs in 2017 (Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	50.83					
ES	16.35					
DE	51.59					
TR	9.19					
TW	100					
NL	19.96					
FR	62.16					
CH	64.52					
IT	43.53					
JP	100					

The efficiency score has been calculated by applying output-oriented models CRS and VRS. The reason for using both models is that the CRS model assumes that all DMUs are operated at optimum size and to be efficient they should meet scale and pure technical efficiency (Emrouznejad et al., 2011). Considering HSRs, this assumption in practice is impossible to fill.

For this reason, the VRS model has been used to examine only pure technical efficiency. The mean values of the PTE of each HSR is calculated by applying the VRS DEA model. The PTE estimated the managerial performance to organize inputs into outputs and disregards the impact of size of scale and compares DMUs only to other units of similar scale (Emrouznejad et al., 2011). Table 7.8 shows the average OTE of CRS output-orientated model by year in percentages. The highest average efficiency score for the selected HSRs was in 2010.

Table 7.9 shows the OTE scores among HSRs, which varies from 6.78% for TR to 95.63% for TW. The TR HSR must increase the number of passengers by 93.22% using the same amount of inputs. Using Tables 7.8 and 7.9, the efficiency of selected HSRs can be compared.

Table 7.8 Efficiency score of DEA CRS output-oriented model for the selected HSRs in period 2010-2017 by year (%) (Source: Author's creation)

HSR	2010	2011	2012	2013	2014	2015	2016	2017
KR	100	100	100	100	100	74.57	75.20	50.83
ES	23.38	17.37	16.19	16.96	17.14	21.55	17.85	16.35
DE	92.97	73.4	75.07	72.97	70.56	83.60	81.20	51.59
TR	7.20	4.22	5.39	6.82	6.29	7.42	7.67	9.19
TW	95.37	88.50	88.39	92.78	100	100	100	100
NL	20.75	18.46	18.59	19.52	13.67	24.15	18.08	19.96
FR	94.36	75.3	72.08	69.83	69.75	71.19	74.13	62.16
CH	54.40	47.25	44.88	52.38	49.49	59.95	67.8	64.52
IT	55.62	51.26	51.42	47.24	38.15	44.18	42.41	43.53
JP	100	86.02	89.49	87.21	91.58	100	100	100
Mean	**64.41**	**56.18**	**56.15**	**56.57**	**55.66**	**58.66**	**58.43**	**51.81**

Table 7.9 Efficiency score of DEA CRS output-oriented model for the selected HSRs in period 2010-2017 by operator (%) (Source: Author's creation)

Year	KR	ES	DE	TR	TW	NL	FR	CH	IT	JP
2010	100	23.38	92.97	7.26	95.37	20.75	94.36	54.40	55.62	100
2011	100	17.37	73.4	4.22	88.5	18.46	75.3	47.25	51.26	86.02
2012	100	16.19	75.07	5.39	88.39	18.59	72.08	44.88	51.42	89.49
2013	100	16.96	72.97	6.82	92.78	19.52	69.83	52.38	47.24	87.21
2014	100	17.10	70.56	6.29	100	13.67	69.75	49.49	38.15	91.50
2015	74.57	21.55	83.60	7.42	100	24.15	71.19	59.95	44.18	100
2016	75.20	17.85	81.20	7.67	100	18.08	74.13	67.80	42.41	100
2017	50.83	16.30	51.59	9.19	100	19.96	62.16	64.52	43.53	100
Mean	87.58	18.35	75.17	6.78	95.63	19.15	73.60	55.08	46.72	94.29

From period 2010-2017 the HSRs operated at different efficiency levels. The mathematical average efficiency score for each of the ten HSRs and average efficiency score per year of the selected HSRs calculated. Inefficient HSRs can improve their efficiency by reducing their level of input or increasing the level of output. Table 7.10 shows average OTE scores for the selected HSRs in the period 2010-2017.

Table 7.10 Average OTE scores of DEA CRS output-oriented model in the period 2010-2017 (Source: Author's creation)

HSR	OTE	Efficiency	Ranking	HSR length in 2017 km	Density of population hab/sq km	GDP per capita in USA$ (2010)
KR	87.58%	N	3	887	527	26152
ES	18.35%	N	9	2852	93	32405
DE	75.17%	N	4	1658	236	46747
TR	6.78%	N	10	724	104	14936
TW	95.63%	N	1	354	655	24292
NL	19.15%	N	8	120	508	53597
FR	73.60%	N	5	2814	122	42576
CH	55.08%	N	6	26869	147	7329
IT	46.72%	N	7	896	205	34877
JP	94.29%	N	2	3041	347	48556
Average	**57.24%**					

E=efficient; N=non-efficient

No HSR was fully efficient throughout the whole selected period. In the period 2010-2014 KR HSR was efficient and from 2015 to 2017 TW HSR was efficient. These HSRs were the efficiency frontier for inefficient HSRs. The TW, KR, and JP HSRs are peers for inefficient HSRs. Referring to Table 7.8 the KR HSR is efficient for the first five years in the selected period and after 2014 efficiency sharply went down to 50.83% in 2017. The TW HSR from 2014 to 2015 increased efficiency and was reported as fully efficient.

The CH HSR has the largest HSR network, but the average performance for the selected period is only 55.08%. There can be seen some fluctuation in the increase in OTE, from 54.04% in 2010 to 64.52% in 2017. There was a slight decrease in OTE in 2014 to 49.49% but it increased to 64.52% by 2017. This can be partially explained by the introduction of another 6300km HSR lines.

The average amount of passenger-km did not increase so fast as the length of the HSR. The smallest average of OTE for the selected period has HSR operators in TR and ES. TR HSR accordingly has an average 6.78% and ES HSR 18.35% of OTE. Operations on HSR in Turkey only began in 2009 and in 2010 its OTE score was 7.26% decreasing the next year to 4.22% with a subsequent increase to 9.19% in 2017. The ES HSR OTE score fluctuated from 23.38% in 2010 to

16.19% in 2012 with subsequent increases to 21.55% in 2015 and decreases in 2017 to 16.35%. An interesting picture can be observed with the KR operator of HSR. The average OTE score for the selected period was 87.58%. In the first part of the selected period (2010-2014) KR HSR was fully efficient, but in the second part of the selected period (2015-2017) OTE score dropped to 50.83%. The FR HSR operator average OTE for the selected period is 73.6%. The OTE dropped from 94.36% in 2010 to 62.16% in 2017. The TW HSR operator has an average OTE for the selected period 95.63% which increased from 88.39% in 2012 to 100% in 2017. The IT HSR operator has an average OTE for the selected period of 46.73% which decreased from 55.62% in 2010 to 43.53% in 2017.

So, if ranking the HSRs for the entire period according to their average score of OTE the best was TW HSR operator followed by JP, KR, DE, FR, CH, IT, NL, ES, TR. Growitsch et al. (2007), found that railways that have a shorter length of network improve efficiency more than railway companies with a large network. Inefficient HSRs can improve their efficiency by increasing the outputs.

To separate inefficient HSRs by category of inefficiency, results from Table 7.5 have been used. Table 7.11 shows the inefficient HSR separated by the category of inefficiency.

Table 7.11 Classification of inefficient HSRs using DEA CRS output-oriented model in the period 2010-2017 (Source: Author's creation)

Category 1	**Category 2**	**Category 3**	**Category 4**
TR =6.78	IT=46.72	FR=73.60	JP=93.29
ES=18.35	CH=55.08	DE=75.17	TW=95.63
NL=19.15		KR=87.58	

The inefficient HSRs have been split into four groups by applying the quartiles approach, where Q1=26.04; Median=64.34; Q3=89.26. Category 1 included HSRs with an inefficiency score below 26.04. In Category 3 included HSRs with scores below 89.26.

The Category 1 includes TR, ES and NL HSRs, who were the worst performers in the selected group of HSRs. There is obvious evidence that current HSR networks of these three HSRs underperforming and there is a lack of the efficiency of resource utilization. The ES and TR HSRs are too large for the current number of passengers, and it needs to look for measures to increase the passenger-km. The NL HSR is a special case, as the UIC doubt that the statistics of the NL HSR operator that was shown on their website are correct.

The HSRs that are included in Category 4 are not fully efficient but operated on a high-level efficiency and can be fully efficient by minor improving the resource utilization process. They scored a value of less than 1, but above the third quartile. Figure 7.5 shows the average technical efficiency scores of the CRS DEA output-oriented model of selected HSRs for the period 2010-2017.

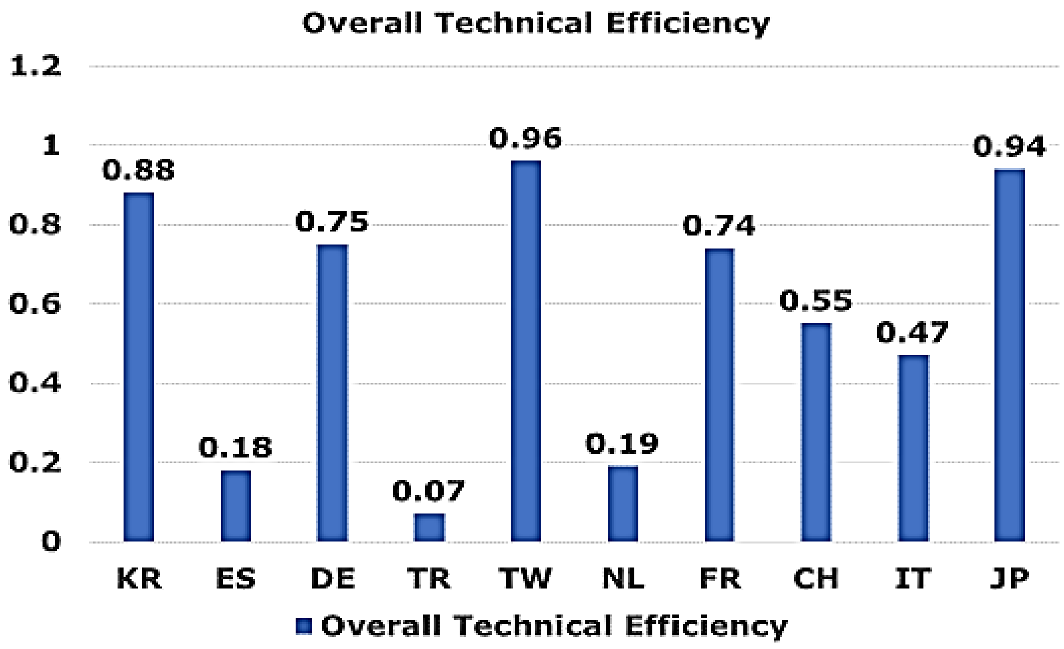

Figure 7.5 The average overall technical efficiency of the selected HSRs using the CRS DEA model (Source: Author's creation)

The overall technical efficiency takes a value between 0 and 1. The value 1 means that HSRs are fully efficient and value 0 means that HSRs are fully inefficient. For KR HSR the technical efficiency is 0.88 it means that the HSR railway in KR is efficient at a level of 88% and this railway could serve the same number of customers with 12% less HSR network or must increase the number of passenger-km to match the efficient frontier.

Countries with the highest GDP per capita have the HSR with the highest OTE score. Regarding the density of population, the four operators that score the highest TE score operate in the top five countries with the highest level of density of population. Also, some researchers concluded that railways that are highly subsidised were relatively less efficient than railways that have less subsides. ES HSR has, on average, €3 billion of government subsidies yearly. The average annual OTE score is an important point of the CRS model. The annual average OTE score presented for each of the eight years shows the changes in the selected period. There is no operator that will be fully efficient throughout the full period. The produced outputs of HSRs in practice can be affected by environmental constraints such as noise level or changes in population density and level of car ownership, etc.

7.2.4 Efficiency trend for the selected HSRs by applying VRS MI DEA output-oriented model

The DEA VRS model assumes that increases in inputs does unnecessary give proportional change in the outputs and its measure of pure technical efficiency (PTE) which is not affected by scale efficiency (SE), where SE=OTE/PTE. The SE shows the Decreasing Return to Scale (DRS), Constant Returns to Scale (CRS) and Increasing Returns to Scale (IRS) (Malikov et al., 2013). The second model chosen for analysis of HSRs is the output-oriented DEA VRS model. Table 7.12 shows the PTE of the selected HSRs in period 2010-2017.

Table 7.12 Efficiency score of DEA VRS output-oriented model for the selected HSRs in the period 2010-2017 by year (%) (Source: Author's creation)

HSR	2010	2011	2012	2013	2014	2015	2016	2017
KR	100	100	100	100	100	81.62	77.76	51.27
ES	23.44	20.10	17.94	19.27	20.04	21.82	17.89	16.36
DE	93.15	81.40	80.72	79.89	78.79	88.67	83.67	51.93
TR	9.39	4.34	5.51	7.00	6.80	8.03	8.03	9.43
TW	98.16	90.99	89.78	95.36	100	100	100	100
NL	100	100	100	100	100	100	100	100
FR	94.60	87.31	79.92	79.29	81.47	71.91	74.53	62.20
CH	97.07	100	100	100	100	100	100	100
IT	55.71	55.39	54.30	50.66	42.49	46.98	43.88	44.36
JP	100	100	100	100	100	100	100	100
Mean	**73.15**	**73.95**	**72.82**	**73.15**	**72.96**	**71.90**	**70.58**	**63.56**

Only two HSRs NL and JP recorded a full efficiency score through the whole observed period. The KR HSR was efficient from 2010 to 2014, and from 2014, efficiency scores dropped to 51.27%. The DE HSR efficiency scores dropped from 93.15% in 2010 to 51.93% in 2017. The CH HSR recorded as efficient from 2011. Tables 7.12 and 7.13 show the efficiency scores of each HSR under the VRS model.

Table 7.13 Efficiency score of DEA VRS output-oriented model for the selected HSRs in the period 2010-2017 by operator (%) (Source: Author's creation)

Year 20..	**KR**	**ES**	**DE**	**TR**	**TW**	**NL**	**FR**	**CH**	**IT**	**JP**
10	100	23.44	93.15	9.39	98.16	100	94.62	97.07	55.71	100
11	100	20.10	81.41	4.34	90.99	100	87.31	100	55.39	100
12	100	17.94	80.72	5.51	89.78	100	79.92	100	54.30	100
13	100	19.27	79.89	7.00	95.36	100	79.29	100	50.66	100
14	100	20.04	78.79	6.80	100	100	81.47	100	42.49	100
15	81.62	21.82	88.67	8.03	100	100	71.91	100	46.98	100
16	77.76	17.89	83.67	8.03	100	100	74.53	100	43.88	100
17	51.27	16.36	51.93	9.43	100	100	62.20	100	44.36	100
Mean	88.83	19.61	79.78	7.32	96.78	100	78.91	99.63	49.22	100

The average efficiency score has been calculated by applying the VRS model and this ranges from 4.34% to 100%, with SD between 32.77 and 37.11. The lowest SD was recorded for 2015 and the highest SD in 2012. The most efficient HSRs were NL, JP, CH, and TW. The lowest efficiency scores belong to TR and ES HSRs. Under the VRS assumption, two inefficient HSRs under the CRS assumption became efficient. For this HSR, OTE was not caused by poor inputs utilization but by the operation of HSR with an inappropriate scale size. Table 7.14 shows the inefficient HSR separated by category of inefficiency.

Table 7.14 Classification of inefficient HSRs using VRS IM DEA output-oriented model in the period 2010-2017 (Source: Author's creation)

Category 1	**Category 2**	**Category 3**	**Category 4**
TR =7.32	IT=49.22	TW=96.78	JP=100
ES=19.61		DE=79.78	NL=100
		FR=78.91	CH=99.63
		KR=88.83	

The efficiency scores of HSRs have been split into four groups by applying the quartiles approach, where Q1=41.82; Median=84.31; Q3=99.72. Category 1 includes HSRs which inefficiency score is below 41.82. Category 3 includes HSRs which score below 99.72. The HSRs that are included in Category 4 are not fully efficient but operated on a high-level efficiency and can be fully efficient by slight improvement in the way their resources are used. They scored a value less than 1 but above the third quartile. Table 7.15 shows the efficiency scores under the VRS output-oriented model.

Table 7.15 Average efficiency scores of HSRs DEA VRS output-oriented model in the period 2010-2017(Source: Author's creation)

HSR	PTE	Efficiency	Ranking	HSR length in 2017 km	Density of population hab/sq km	GDP per capita in USA$ (2010)
KR	88.83%	N	4	887	527	26152
ES	19.61%	N	8	2852	93	32405
DE	79.78%	N	5	1658	236	46747
TR	7.32%	N	9	724	104	14936
TW	96.78%	N	3	354	655	24292
NL	100%	E	1	120	508	53597
FR	78.91%	N	6	2814	122	42576
CH	99.63%	N	2	26869	147	7329
IT	49.22%	N	7	896	205	34877
JP	100%	E	1	3041	347	48556
Average	72.01					

E=efficient; N=non-efficient

For the selected period under VRS model there are four operators of HSRs that are efficient NL, DE, CH, JP and followed by KR, FR, TW, IT, ES, TR. During the study period 2010-2017 KR HSR scored 89.80% of efficiency, it means that KR could have produced the same amount of output by using only 89.80% of inputs. The JP and NL HSRs are efficient under VRS. Figure 7.6 shows the mean PTE of the selected HSRs for the period 2010-2017. If there is a difference between the OTE and PTE scores of a specific HSR, then it means that there is a scale of inefficiency.

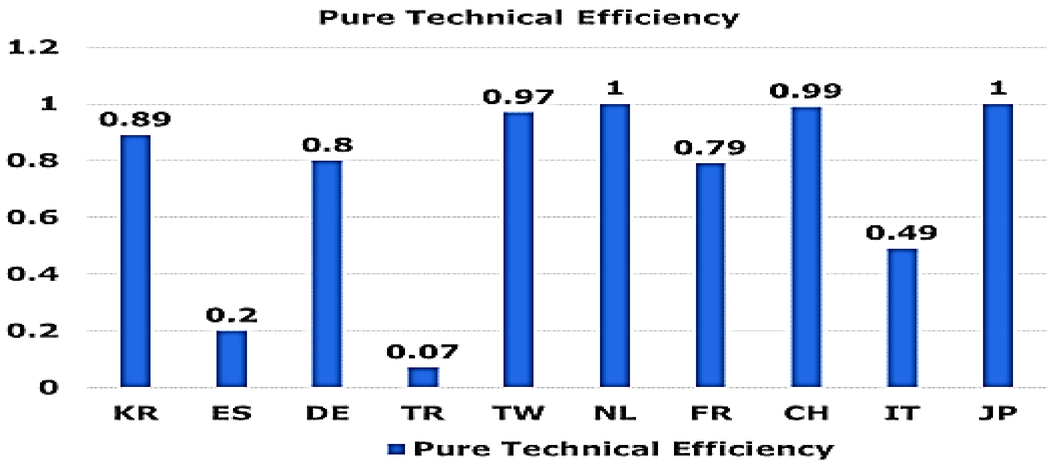

Figure 7.6 The mean pure technical efficiency score of the DEA VRS output-oriented model (Source: Author's creation)

7.2.5 Comparison of efficiency scores CRS-MI vs VRS-MI DEA models

To investigate the difference in CRS and VRS scores for selected HSRs in the period 2010-2017 a comparative table was built. Table 7.16 shows the comparative score of MI (CRS-MI vs. VRS-MI) over the selected period 2010-2017.

Table 7.16 Comparative efficiency scores of MI (CRS-MI vs VRS-MI) in the selected period 2010-2017 (%) (Source: Author's creation)

Year		KR	ES	DE	TR	TW	NL	FR	CH	IT	JP
2010	CRS	100	23.38	92.97	7.26	95.37	20.75	94.36	54.40	55.62	100
	VRS	100	23.44	93.15	9.39	98.16	100	94.62	97.07	55.71	100
2011	CRS	100	17.37	73.40	4.22	88.50	18.46	75.30	47.25	51.26	86.02
	VRS	100	20.10	81.41	4.34	90.99	100	87.31	100	55.39	100
2012	CRS	100	16.19	75.07	5.39	88.39	18.59	72.08	44.88	51.42	89.49
	VRS	100	17.94	80.72	5.51	89.78	100	79.92	100	54.30	100
2013	CRS	100	16.96	72.97	6.82	92.78	19.52	69.83	52.38	47.24	87.21
	VRS	100	19.27	79.89	7.00	95.36	100	79.29	100	50.66	100
2014	CRS	100	17.14	70.56	6.29	100	13.67	69.75	49.49	38.15	91.58
	VRS	100	20.04	78.79	6.80	100	100	81.47	100	42.49	100
2015	CRS	74.57	21.55	83.60	7.42	100	24.15	71.19	59.95	44.18	100
	VRS	81.62	21.82	88.67	8.03	100	100	71.91	100	46.98	100
2016	CRS	75.20	17.85	81.20	7.67	100	18.08	74.13	67.80	42.41	100
	VRS	77.76	17.89	83.67	8.03	100	100	74.53	100	43.88	100
2017	CRS	50.83	16.35	51.59	9.19	100	19.96	62.16	64.52	43.53	100
	VRS	51.27	16.36	51.93	9.43	100	100	62.20	100	44.36	100

According to Table 7.16 all CRS-MI scores for the selected HSRs are lower than that of VRS-MI. This is due to a large standard deviation (SD) in variables such as network length and number of passengers and passenger-km. The highest efficiency score in both cases (CRS-MI and VRS-MI) have TW, JP, and KR HSRs which in some years of the selected period have 100% and classified as efficient HSRs. In the selected period, the score of NL HSR is very different in CRS-MI and VRS-MI this can be due to the input data. The maximum observed SD in 2010 for the HSRs is found within a range of 0.06% to 79.28%, and for 2017 within a range of 0.01% to 80.04%. The NL HSR had the highest gap in scores for the selected period 2010-2017.

The JP HSR under the assumption of VRS is the most technically efficient HSR, but under CRS assumption its efficiency varies between 86.02% and 100%. This is due to a low scale efficiency during the selected period. The CH HSR under VRS assumption is the technically efficient system, but under CRS assumption technical efficiency varies between 44.88% and 67.8%. This demonstrates that in the selected period, its operational scale (or PTE) was only between 44.88% and 67.8% of its maximum efficiency. The results suggest that in the selected period, 2010-2017 supply for HSR services is higher than demand. The CH HSR expanded rapidly, and their railway network is the largest in the world. The TW HSR for the period 2014-2017 scored 100% efficiency in both models and can be classified as technically and scale efficient.

7.2.6 Mean efficiency scores for the selected HSRs

The OTE measure is a combined measure of pure technical efficiency (PTE) and scale efficiency (SE). The PTE measure is obtained from the VRS output-oriented model (Fu et al., 2018). The decomposition of the overall technical efficiency (OTE) into pure technical efficiency (PTE) and scale efficiency (SE) is represented in Table 7.17. The ratio of CRS efficiency scores over the VRS efficiency scores gives the scale efficiency. The SE is the ratio of OTE to PTE. The measure of SE shows how the size of the railway network (too large or too small) influences OTE.

Table 7.17 shows that scale inefficiency dominates the pure technical inefficiency of HSRs. This means that the operations of HSRs were at the wrong scale. Table 7.17 represents a summary of annual means of change in OTE, PTE, and SE for all ten HSRs. It is seen from table 7.17 that in period 2010-2017 all the HSRs have an inefficiency in case of Overall Technical Efficiency (OTE) within a range of 4.37% to 93.22%. In case of PTE two HSRs for period 2010-2017 has been efficient, they are NL and JP. For two HSRs that became efficient under VRS assumption, the OTE was not affected by poor input utilization (managerial inefficiency) but by an inappropriate size of scale.

For the remaining eight HSRs OTE is affected by managerial inefficiency and scale inefficiency, but on a different magnitude as they have PTE and SE less than 1. The scale efficiency shows what can be achieved if HSRs were the optimum size and whether there will be increases or decreases in returns to scale and by increasing or reducing the scale HSR, can increase its efficiency.

Investigating the scale efficiency was achieved by comparing two different outputs of the DEA models. The first output is CRS, using the assumption of constant return to scale and second output is VRS, variable returns to scale (Emrouznejad et al., 2011). Comparing the CRS and VRS outputs is possible to see that HSR networks are either too large or too small or they operate at its optimal size.

Table 7.17 shows the mean efficiency and inefficiency scores for the selected HSRs for the period 2010-2017, where:

- OTIE% = Overall Technical Inefficiency, which is =(1-OTE) x100
- PTIE% =Pure Technical Inefficiency, which is =(1-PTE) x100
- SIE% =Scale Inefficiency, which is=(1-SE) x100
- RTS-Returns-to-Scale
- IRS-Increased Returns-to-Scale
- DRS-Decreased Returns-to-Scale
- CRS-Constant Returns-to-Scale

Table 7.17 Mean efficiency scores of selected HSRs in the period 2010-2017 (Source: Author's creation)

HSR	OTE (CRS)	OTIE (%)	PTE (VRS)	PTIE (%)	SE	SIE (%)	RTS For 2017	HSR length in 2017 (km)
KR	0.8758	12.42	0.8883	11.17	0.9859	1.41	IRS	887
ES	0.1835	81.65	0.1916	80.39	0.9357	6.43	IRS	2852
DE	0.7517	24.83	0.7978	20.22	0.9422	5.78	IRS	1658
TR	0.0678	93.22	0.0732	92.68	0.9262	7.38	IRS	724
TW	0.9563	4.37	0.9678	3.22	0.9881	1.19	CRS	354
NL	0.1915	80.85	1	0	0.1915	80.85	IRS	120
FR	0.7360	26.40	0.7891	21.09	0.9327	6.73	IRS	2814
CH	0.5508	44.92	0.9963	0.37	0.5528	44.72	DRS	26869
IT	0.4672	53.28	0.4922	50.78	0.9492	5.08	IRS	896
JP	0.9429	5.71	1	0	0.9429	5.71	CRS	3041
Mean	0.5724	42.77	0.7201	27.99	0.8347	16.53		4021.5

The PTIE means that HSR has more inputs than is necessary to produce outputs. The SIE can be caused by regulatory policy induced to expand the HSR network beyond the economically profitable size. One example of this can be the high number of HSR stations in France, where local authorities insist on the necessity of them. At the end, HSR has stations that were not economically appropriate from the HSR point of view. The OTIE affecting the productivity growth and one reason of the appearance of OTIE can be that HSR is protected from competition by regulation and some HSRs may not be motivated to control costs.

According to Table 7.17 the KR, ES, DE, TR, TW, FR, and IT HSRs had PTE scores less than the SE score. This indicated that their inefficiency is primarily related to the managerial inefficiency, such as technological inefficiency or the decision on resources distribution rather than the scale inefficiency. The results for ES show that SE (operational scale) is near 100% and it does not make a serious contribution to the OTIE which is 81.65%. Rather, PTIE has the largest effect which is 80.39% or it can be the resource allocation ineffectiveness.

To minimize the costs and maximise revenue, HSRs should operate at their most productive scale size. Application of RTS helps to find how the size of scale will influence productivity. The scale inefficiency is observed if the RTS can take two forms: increasing returns-to-scale or decreasing returns-to-scale. Increasing RTS means that HSRs can gain efficiency by increasing outputs. Decreasing RTS means that a reduction in the scale of HSRs increases efficiency. HSR is scale efficient if it operates at constant return-to-scale. This occurs when OTE=PTE. All efficiency measures lie between 0 and 1. The nature of RTS can be defined from the magnitude of optimal $\Sigma\lambda$ in the CRS model (Ahmad at el.,2017):

If $\Sigma\lambda=1$, then HSR is efficient and has constant returns-to-scale.

If $\Sigma\lambda<1$, then HSR is inefficient due to increasing returns-to-scale.

If $\Sigma\lambda>1$, then HSR is inefficient due to decreasing returns-to-scale.

For 2017, the two HSRs (TW and JP) have CRS, which means that they are scale efficient. Some HSRs may require an increase in output or decrease in input to achieve better performance. The IRS is a predominate form of scale inefficiency in selected HSRs. Seven of the HSRs have IRS and by increasing the output will improve the OTE. The following HSRs need to increase output to attain better performance and they are KR, ES, DE, TR, NL, FR, IT, but the CH HSR needs to reduce in scale to achieve efficiency. The TW and JP HSRs show the Constant Returns-to-Scale.

The mean PTE score for ten HSRs was 0.7201 with a standard deviation (SD) of 0.35, whereas the mean scale efficiency of selected HSRs was 0.8347 with SD of 0.26. The lower mean and higher SD of the PTE score compared to the SE score indicated that a larger portion of overall technical inefficiency for selected HSRs was due to the PTE.

The highest mean scale efficiency score is recorded for TW and the lowest score was NL and CH. The results show that CH used an inappropriate size of their sources. Table 7.17 shows that means PTE and SE of all HSRs over the selected period is 72.01% and 83.47% respectively. The results of output-oriented CRS and VRS DEA models in Table 7.17 indicates that no HSRs were efficient throughout the 2010-2017 period.

The size of operations affects OTE. In Europe, the highest score of PTE is 0.7978 for DE HSR and lowest 0.0732 for TR HSR. In Asia, the highest score for PTE is for JP HSR, which is 1 and lowest for KR HSR with 0.8883. In Asia HSRs have higher PTE scores than in Europe, it can be explained that in Asia the technical efficiency of HSRs is less affected by the size of the network.

Table 7.17 shows the large asymmetry between HSRs regarding to their OTE that range between 0.0678 and 0.9563. The average score of OTE for ten HSRs was 0.5724. This suggests that an average HSR, with its current length of network, produces only 57.24% of its outputs compared to the efficient frontier. Adapting the best practice technology HSRs can, on average, increase the passenger-km by 42.77% without increasing the length of current networks. However, the potential increase of output for selected HSRs varies between 93.22% and 4.37%. The selected group of HSRs do not have a fully efficient HSR, since the average OTE score of HSRs are less than 1.

7.2.7 Descriptive statistics of mean efficiency scores

Table 7.18 shows descriptive statistics of the selected group of HSRs, NL is not included. The results of a DEA approach show that the score of OTIE for selected HSRs is influenced by poor input utilization (PTIE) and lack of success to operate at their most productive scale size (SIE). The average PTE score for selected HSRs is 0.6885 that means that 31.15% (PTIE) of the 38.53% (OTIE) is due to the HSRs managerial inefficiency. The 7.38% is the rest of OTIE and seems due to an inappropriate scale size. The lower mean 0.6885 and a high standard deviation 0.3528 of PTE compared to SE that have a mean of 0.9062 and standard deviation of 0.1314 indicate that PTE has a higher influence on OTE than SE.

Table 7.18 Descriptive statistics of mean efficiency scores of the selected HSRs in the period 2010-2017 (Source: Author's creation)

Statistics	OTE	OTIE	PTE	PTIE	SE	SIE
N	9	9	9	9	9	9
Mean	0.6227	38.53	0.6885	31.15	0.9062	9.38
SD	0.3448	32.34	0.3528	35.20	0.1314	13.44
Minimum	0.0678	4.37	0.0732	0.00	0.5528	1.19
Q_1	0.3963	12.42	0.4922	3.22	0.9327	5.08
Median	0.7439	26.40	0.7978	20.22	0.9422	5.78
Q_3	0.8926	53.28	0.9678	50.78	0.9422	6.73
Maximum	0.9563	93.22	1.00	92.68	0.9881	44.72

7.2.8 Mean efficiency scores of HSRs by region

Table 7.19 shows the OTE scores for selected HSRs in Europe (NL not included), HSRs in Asia and all HSRs.

Table 7.19 The mean Overall Technical Efficiency scores by region under CRS (Source: Author's creation)

Year	In Europe HSR	In Asia HSR	All HSR
2010	0.5472	0.8744	0.6926
2011	0.4431	0.8044	0.6037
2012	0.4403	0.8069	0.6032
2013	0.4276	0.8309	0.6068
2014	0.4038	0.8527	0.6033
2015	0.4559	0.8363	0.6250
2016	0.4465	0.8575	0.6292
2017	0.3656	0.7884	0.5535
2010-2017	**0.4413**	**0.8314**	**0.6227**

In Table 7.19 the mean values of OTE calculated under CRS by solving CCR DEA model and that OTE score of all HSRs for the selected period 2010-2017 is 0.6227, which show that HSRs could have 37.73% more of output to have the same amount of input. In Europe, the highest score of OTE was 0.5472 and in Asia 0.8744. The lowest score of OTE for HSRs in Europe was 0.3656 and in Asia it was 0.7884.

Figure 7.7 shows a tendency in the mean OTE scores by regions. The mean OTE scores had the same pattern for both regions. In both regions, there can be observed a slight decrease in mean OTE scores from 2010 to 2014 and with subsequent improvements from 2014 to 2016. After 2016 there was observed a decrease in OTE.

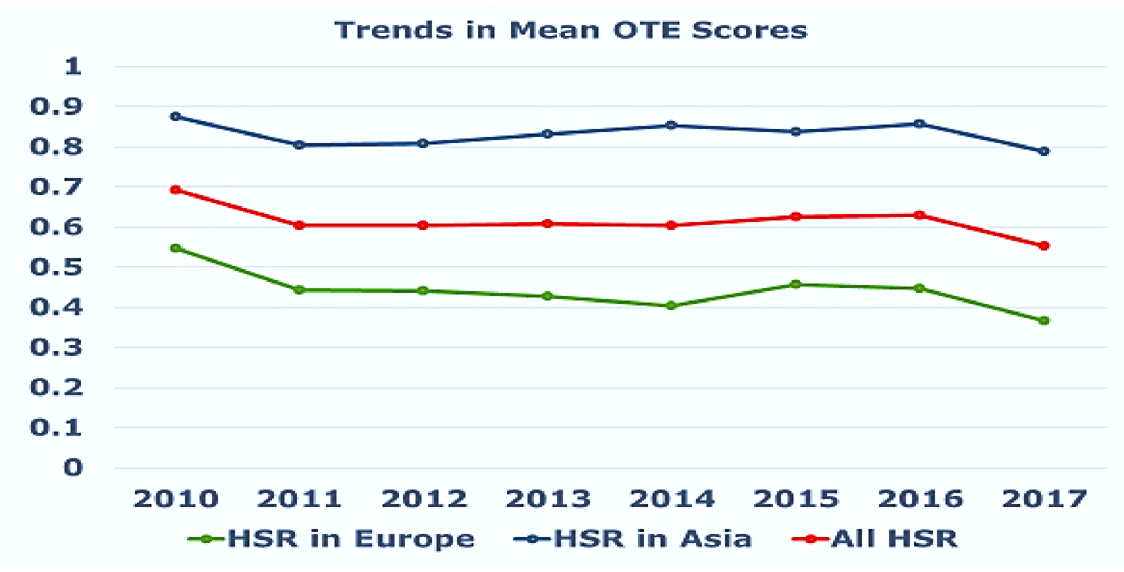

Figure 7.7 Trends in mean OTE scores (Source: Author's creation)

PTE indicates that the HSRs can transport more passengers using existing technology. Table 7.20 shows that PTE scores in Asian regions are higher than for selected HSRs in Europe.

Table 7.20 The mean Pure Technical Efficiency scores by region (Source: Author's creation)

Year	In Europe HSR	In Asia HSR	All HSR
2010	0.5526	0.9881	0.7461
2011	0.4971	0.9775	0.7105
2012	0.4768	0.9745	0.6980
2013	0.4722	0.9884	0.7015
2014	0.4592	1.0000	0.6994
2015	0.4748	0.9541	0.6878
2016	0.4560	0.9444	0.6731
2017	0.3686	0.8782	0.5951
2010-2017	**0.4697**	**0.9631**	**0.6885**

The mean PTE score is higher for HSRs in Asia than for HSRs in Europe. The mean PTE score for HSRs in Europe is continuously decreasing from 2010 to 2014 and from 2014 it slightly increased but from 2015 decreases again. For HSRs in Asia, the mean PTE score has been increased from 2012 to 2014, and after 2014 it has an obvious decrease. Figure 7.8 shows a tendency in the mean PTE score by regions.

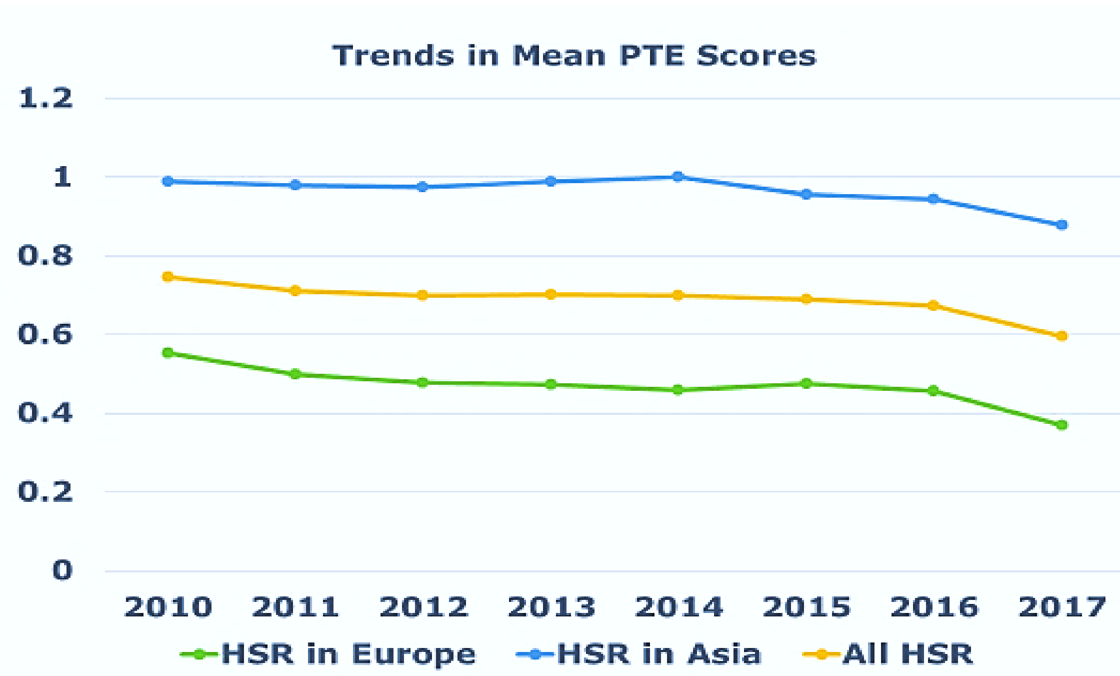

Figure 7.8 Trends in mean PTE scores (Source: Author's creation)

7.2.9 Scale efficiency scores for the selected HSRs

Scale efficiency shows that the HSR is operated at its optimal size or not. If SE is 1, it means that HSRs need not increase or decrease the scale of its operations. Inefficiency occurs when HSRs use to many inputs and produce too little outputs, which is managerial inefficiency. Table 7.21 shows the SE scores for the selected HSRs. The SE ratio varies between 0 and 1, and the operational scale is inefficient if, 0≤SE<1 (Emrouznejad et al., 2011).

Table 7.21 Scale efficiency scores for the selected HSRs (Source: Author's creation)

HSR	2010	2011	2012	2013	2014	2015	2016	2017
KR	1	1	1	1	1	0.9136	0.9670	0.9914
ES	0.9974	0.8641	0.9024	0.8801	0.8552	0.9876	0.9977	0.9993
DE	0.9980	0.9016	0.9300	0.9133	0.8955	0.9428	0.9704	0.9934
TR	0.7731	0.9723	0.9782	0.9742	0.9250	0.9240	0.9551	0.9745
TW	0.9715	0.9726	0.9845	0.9729	1	1	1	1
NL	0.2075	0.1846	0.1859	0.1925	0.1367	0.2415	0.1808	0.1996
FR	0.9972	0.8624	0.9019	0.8806	0.8561	0.9899	0.9946	0.9993
CH	0.5604	0.4725	0.4486	0.5238	0.4949	0.5995	0.6780	0.6452
IT	0.9983	0.9254	0.9469	0.9324	0.8978	0.9404	0.9664	0.9812
JP	1	0.8602	0.8949	0.8721	0.9158	1	1	1

Table 7.22 shows the mean SE scores by regions. The SE scores for HSRs in Europe are higher than for HSRs in the Asian region. The mean PTE scores of

all HSRs were decreasing from 0.7461 in 2010 to 0.5951 in 2017. The main SE scores increased from 0.9218 in 2010 to 0.9538 in 2017.

Table 7.22 Mean scale efficiency scores by regions (Source: Author's creation)

Year	Europe HSR	Asia HSR	All HSR Mean
2010	0.9528	0.8830	0.9218
2011	0.9052	0.8263	0.8701
2012	0.9319	0.8320	0.8875
2013	0.9161	0.8422	0.8833
2014	0.8859	0.8527	0.8711
2015	0.9569	0.8783	0.9229
2016	0.9768	0.9113	0.9477
2017	0.9895	0.9092	0.9538
2010-2017	**0.9394**	**0.8669**	**0.9062**

Figure 7.9 shows a tendency in the mean SE scores by region. Most HSRs in the selected groups have scale problems, the inputs have not been fully utilized.

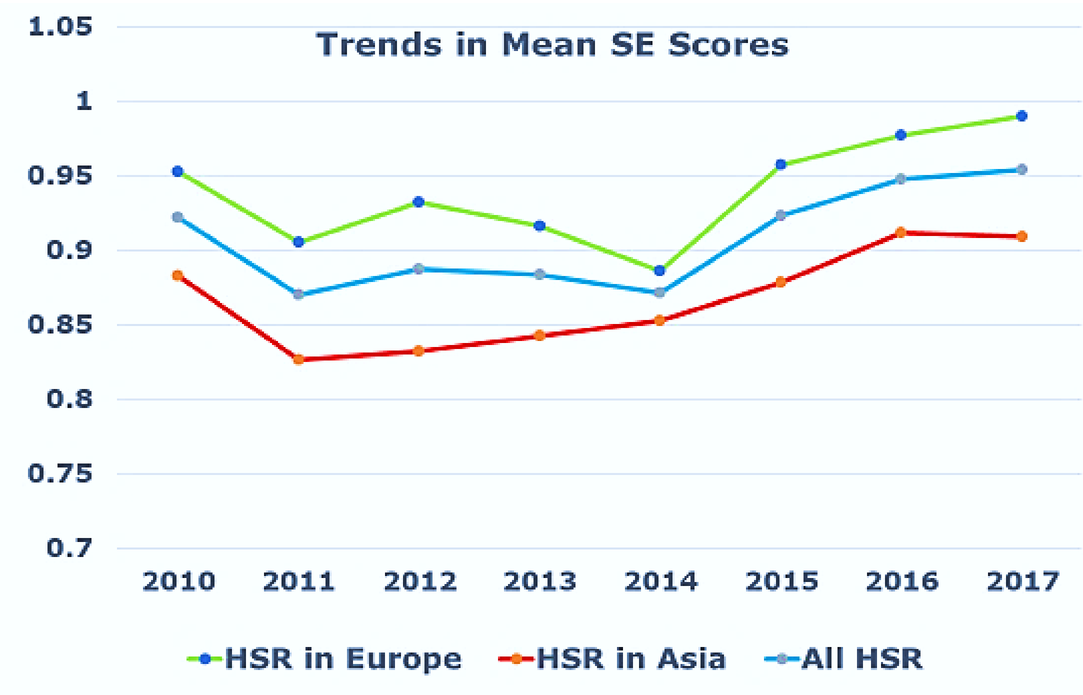

Figure 7.9 Trends in mean SE scores (Source: Author's creation)

Figure 7.9 shows that the HSRs in Asia has a lower SE than HSRs in Europe. In Asia, inputs have been better utilized than in Europe.

7.2.10 Lambda of CRS MI DEA output-oriented model

The Lambda value were represented for each of the individual HSRs for each of the periods. The Lambda defines the amount of outputs to be increased by an inefficient HSR to reach their peers which are operating efficiently. The Lambda results for period 2010-2017 of CRS MI DEA simulation is in Appendix B. Table 7.23 shows the value of Lambda for selected HSRs to reach their peers (TW and JP HSRs) in 2017.

Table 7.23 Lambda of CRS MI DEA for 2017 (Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	TW	JP				
KR	0.43	0.24				
ES	0	0.94				
DE	0	0.55				
TR	0	0.24				
TW	1	0				
NL	0.34	0				
FR	0	0.93				
CH	0	8.84				
IT	0	0.29				
JP	0	1				

Lambda helps to find a target. The Lambda values for period 2010-2016 is presented in Table 7.24.

From Table 7.24 it can be found that Peers have Lambda values 1 or 0. The highest Lambda value belongs to CH HSR. It means that to be efficient, the CH HSR needs to have larger improvements than other HSRs.

Table 7.24 Lambda values for the period 2010-2016 (Source: Author's creation)

HSR	2010		2011	2012	2013	2014		2015		2016	
	KR	JP	KR	KR	KR	KR	TW	TW	JP	TW	JP
KR	1	0	1	1	1	1	0	0.10	0.20	0.34	0.18
ES	4.56	0	4.77	4.90	5.20	5.17	0	0	0.67	0	0.85
DE	2.34	0	2.34	2.34	2.39	2.39	0	0	0.31	0	0.34
TR	0	0.09	1.20	1.20	1.20	1.71	0	0	0.25	0	0.25
TW	0	0.13	0.93	0.96	0.93	0	1	1	0	1	0
NL	0	0.05	0.33	0.33	0.33	0	0.35	0	0.04	0.34	0
FR	5.01	0	5.03	5.03	5.03	5.03	0	0	0.72	0	0.74
CH	0	1.78	16.5	22.9	28.3	39.6	0	0	6.60	0	6.90
IT	1.86	0	1.77	1.77	1.83	2.32	0	0	0.30	0	0.31
JP	0	1	7.10	7.10	7.10	5.60	1.96	0	1	0	1

7.2.11 Peers of CRS MI DEA output-oriented model

DEA identifies the best practice 'Peer' from the set of similar units and estimates the efficiency of HSRs by comparing to the best practice HSR chosen from its peers. The peer group can be used to understand the most efficient DMUs. For 2017, the most efficient HSR was JP, as it is the peer for eight from ten HSRs. The peers of the model can be used to identify the aspects of poor performance of the corresponding inefficient DMU. The level of input/output of a peer can indicate target level for input/output inefficient DMU (Emrouznejad et al., 2011).

Table 7.25 shows the benchmarks for each of the HSRs in 2017. The TW and JP HSRs are the peers of the selected model. The fully efficient HSRs consider itself to be its own peer. For example, JP is the benchmark for JP. For ES HSR, the JP HSR is the benchmark. HSR needs to use a combination from these peers to become efficient. For the year 2010, the most efficient peers were found in TW and JP HSRs with a frequency score of five. In 2017, changes were observed in peers of model. The most efficient peer frequency is found in the JP HSR with a score of eight and second the most efficient peer frequency is observed in the TW HSR with a score of three. The JP HSR is the most significant DMU for the calculation of efficiency. The peer's results for period 2010-2017 of CRS MI DEA simulation is in Appendix B. Table 7.25 shows the frequency of peers for inefficient HSR in 2017. The TW HSR appears three times as a peer and JP HSR eight times.

Table 7.25 Frequency of peers in 2017 (Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	TW	JP				
(Frequenc	3	8				
KR	True	True				
ES	False	True				
DE	False	True				
TR	False	True				
TW	True	False				
NL	True	False				
FR	False	True				
CH	False	True				
IT	False	True				
JP	False	True				

For 2017, two HSRs are efficient, but to understand which of them perform better, the observation of peers' frequency can be used. The HSR that peers mostly are the best performer from two. In the case of 2017, it is JP HSR. The Table 7.26 shows the frequency of peers for the period 2010-2017.

Table 7.26 Peers frequency for the period 2010-2017 (Source: Author's creation)

HSR	2010	2011	2012	2013	2014	2015	2016	2017
KR	5	10	10	10	8	----	----	----
ES	----	----	----	----	----	----	----	----
DE	----	----	----	----	----	----	----	----
TR	----	----	----	----	----	----	----	----
TW	----	----	----	----	3	2	3	3
NL	----	----	----	----	----	----	----	----
FR	----	----	----	----	----	----	----	----
CH	----	----	----	----	----	----	----	----
IT	----	----	----	----	----	----	----	----
JP	5	----	----	----	----	9	8	8

From Table 7.26 it can be found that only three HSRs were efficient in some years. The KR HSR was efficient from 2010 to 2014, TW HSR was efficient from 2014 to 2017 and JP HSR was efficient in 2010 and from 2015 to 2017.

7.2.12 Targets of CRS MI DEA output-oriented model

The DEA, apart from determining the efficiency score of HSR, will find the target values of input and output for an inefficient HSR. The efficiency targets show how much inputs can be decreased, and outputs increased to make the HSRs efficient. For 2010 two HSRs were efficient KR and JP and they do not need improvements compared to other selected HSRs. The TW HSR needed an increased number of passengers by 4.86%, from 36939 thousand passengers to 38733,89 thousand. For 2017, two HSRs were efficient, TW and JP.

The rest of the selected HSRs need to improve their performance to match efficient HSRs. The KR HSR needs to improve performance from 59669 thousand passengers to 1173994.37 thousand, almost double the performance to match JP HSR. Table 7.27 shows the targets value of input and outputs for inefficient HSRs in 2017. These targets need to be reached by HSRs to be on the frontier line. The target results for period 2010-2017 of CRS MI DEA simulation is in Appendix B. Table 7.27 shows the target values of input and outputs for an inefficient HSRs in 2017.

Table 7.27 Target values of input and output for inefficient HSRs in 2017(Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection	Categoric	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line Gain(%)	
KR	59669	117394.4	96.74	14869	29253.66	96.74	887	887	0	
ES	40259	354266	779.97	15540	95027.59	511.5	2852	2852	0	
DE	86732	205951.3	137.46	28502	55243.95	93.82	1658	1658	0	
TR	7160	89932.89	1156.05	2218	24123.41	987.62	724	724	0	
TW	60570	60570	0	11103	11103	0	354	354	0	
NL	4098	20532.2	401.03	413	3763.73	811.31	120	120	0	
FR	108720	349545.8	221.51	58280	93761.44	60.88	2814	2814	0	
CH	1517800	3337579	119.9	577635	895265.2	54.99	26869	26869	0	
IT	41276	111298.2	169.64	12997	29854.39	129.7	896	896	0	
JP	377743	377743	0	101325	101325	0	3041	3041	0	

Table 7.27 shows that input values have not changed. If the KR HSR network stays the same, to be efficient, KR HSR needs to increase output from 59669 to 117394 thousand passengers. The TR and ES HSRs must have the highest increase in output value to be efficient.

7.2.13 Slacks of CRS MI DEA output-oriented model

Slack is calculated after the efficiency score is found. HSR is efficient if efficiency score is equal 1 and slack score is equal 0. HSR will be weakly efficient if efficiency score is equal 1 but slack has a non-zero value (Kastaniotis et al., 2012). The presence of non-zero slacks shows that HSRs can improve their performance over the level estimated by technical efficiency. In the output-oriented DEA model, the slack shows how further can be increased in outputs (Emrouznejad et al., 2011).

Table 7.28 shows the value of slacks by which is needed to increase outputs of inefficient HSRs over the level estimated by TE in 2017. ES, DE, TR, FR, CH, and IT HSRs need to increase the number of passengers, but NL HSR needs to increase the number of passenger-km. Only one HSR has a zero value of slack- the efficient HSR, TW.

Table 7.28 Slacks of inefficient HSRs in 2017 (Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	108081	0	0			
DE	37843.16	0	0			
TR	12059.3	0	0			
TW	0	0	0			
NL	0	1694.48	0			
FR	174636	0	0			
CH	985170.1	0	0			
IT	16486.3	0	0			
JP	0	0	0			

7.2.14 Weights of CRS MI DEA output-oriented model

The DEA model calculates the combination of inputs and outputs weight for each HSR to maximise their productivity ratio and optimise the HSR score by varying the weights that applies to each input and output. The efficiency of a DMU equal: weight sum of the output variables/weight sum of the input variables (Emrouznejad et al., 2011).

The weight describes the importance of different factors and always has a positive value. The maximum value of weight is 1 (Emrouznejad et al., 2011). The weights result for period 2010-2017 of CRS MI DEA simulation is in Appendix B. Table 7.29 shows that the size of HSR network in TR and NL in 2017 have influenced the analysis. The higher the value of weight, the stronger influence in the analysis on efficiency values. The size of the TR and NL HSRs networks contribute at least 0.02 and 0.04 respectively of the total output to determine HSR efficiency.

Table 7.29 Weights of CRS MI DEA output-oriented model for 2017 (Source: Extract from DEA simulation)

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.02			
TW	0	0	0			
NL	0	0	0.04			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Throughout the whole period 2010-2017 the scale of NL and TR has an influence on the efficiency of these HSRs.

7.2.15 Production Possibility Set (PPS) chat for 2017 CRS MI DEA model

Figure 7.10 shows the distance of the DMUs (HSRs) to the efficiency boundary. The two HSRs; TW and JP lie on the boundary and classified as efficient DMUs in 2017. Where: X- inputs, length of HSR network; Y_1- outputs, number of passengers; Y_2-outputs, passenger-km.

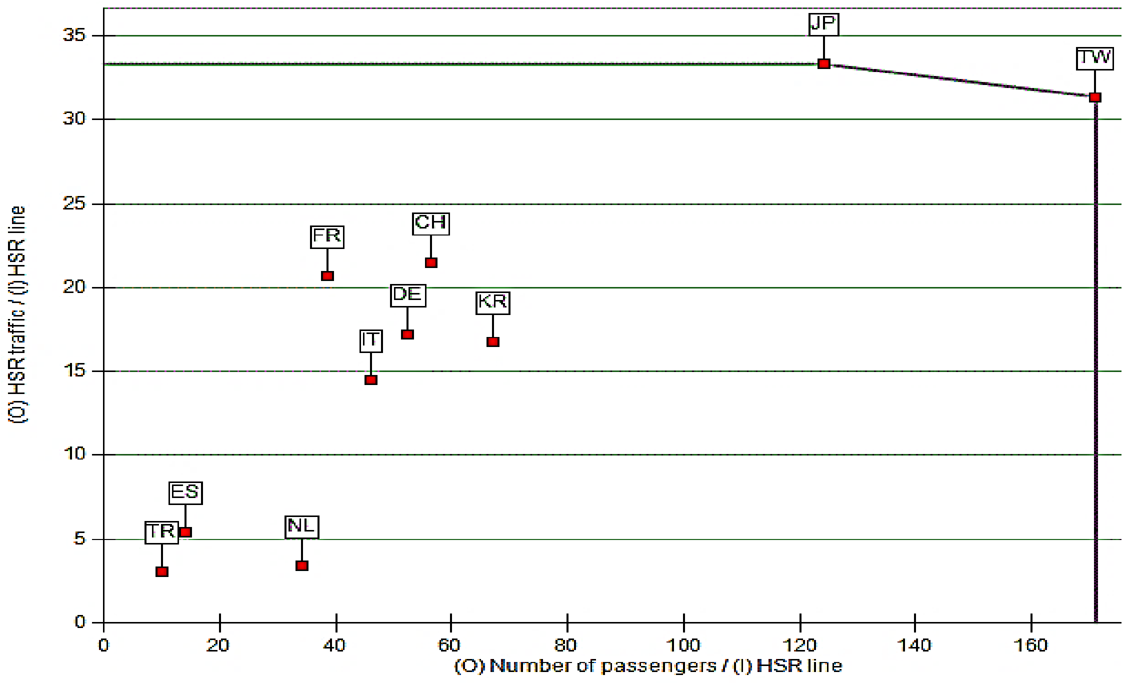

Figure 7.10 PPS chat for 2017 CRS MI DEA model (Source: Extract from DEA simulation)

From PPS chat for 2017 it can be observed that the performance of TW and JP HSRs have much higher productivity than the rest of selected HSRs. In the whole observed period 2010-2017 the weakest performers were TR, ES, NL HSRs

7.2.16 Slacks, targets, and potential improvements for the selected HSRs

The slacks, targets and potential improvements are shown in Table 7.30.

Table 7.30 Slacks and targets for inefficient HSRs for 2017

HSR	OTIE	Slacks			Targets			Potential Improvements		
		X	Y_1	Y_2	X	Y_1	Y_2	X	Y_1	Y_2
KR	49.17	0	0	0	0	117394.37	29253.66	0	117394.37	29253.66
ES	83.65	0	108081.00	0	0	354266.04	95027.59	0	462347.04	95027.59
DE	48.41	0	37843.16	0	0	205951.30	55243.95	0	243794.46	55243.95
TR	80.81	0	12059.30	0	0	89932.89	24123.41	0	101992.19	24123.41
TW	0	0	0	0	0	60570.00	11103.00	0	60570.00	11103.00
NL	80.04	0	0	1694.48	0	20532.20	3763.73	0	20532.20	5458.21
FR	37.84	0	174636.00	0	0	349545.65	93761.44	0	524181.65	93761.44
CH	35.48	0	985170.10	0	0	333757865	895265.18	0	334743035.10	895265.18
IT	56.47	0	16486.30	0	0	111298.17	29854.39	0	127784.47	29854.39
JP	0	0	0	0	0	377743.00	101325.00	0	377743.00	101325.00

Table 7.30 gives the input and output slacks obtained from the CCR model for eight inefficient HSRs,

where:

X- inputs, length of HSR network.

Y_1-outputs, number of passengers.

Y_2-outputs, passenger-km.

OTIE is Overall Technical Inefficiency of selected HSRs.

For 2017 the percentage of OTIE, the smallest is for CH HSR and if the number of passengers and passenger-km will increase by 35.48% CH HSR will became efficient. The highest OTIE score was found to be for ES, which is 83.65%.

7.3 Extract from IBM SPSS analysis

To investigate the relationship between OTE and Productivity with selected factors, IBM SPSS software was employed.

7.3.1 Selected factors that affect the performance of HSRs

To select factors that can affect the sustainability of HSR reference was made to several previous papers that analysed different factors influencing the sustainability of HSR. For this research, there were 17 factors selected that can influence the performance of HSR. The factors were allocated into three groups. The first group of collected factors is related to economic sustainability, the second group is related to environmental sustainability, such as electric power consumption. In the third group, there were collected factors related to the social sustainability of HSR, such as density of population and GDP per capita. Table 7.31 shows the selected factors influencing the performance of HSR.

Table 7.31 Selected factors influencing performance of HSR (Source: Author's creation)

Group1- Economic Sustainability	**Group2- Environmental Sustainability**	**Group3- Social Sustainability**
Level of productivity	Annual electric power consumption	Surface area of country
Overall Technical Productivity	Passenger-km	Population of selected countries
Length of HSR lines	Average traction power per train	Density of population
Average distance per passenger	Number of HS train sets	GDP per capita
Average time in vehicle	Total number of seats	Land taking by HSR
Number of passengers	Average number of seats per train	Mean Annual Staff Numbers

Table 7.32 shows the variables from Group 1 related to the economic sustainability of HSRs for 2017.

Table 7.32 Variables related to economic sustainability of HSRs for 2017(Source: Extract from SPSS simulation)

HSR	Level of Productivity of HSR	Overall Technical Efficiency	Length of HSR lines	Average Distance per Passenger	Average Time in Vehicle	Number of Passengers
KR	1.21	50.83	887.00	249.00	1.61	59669.00
ES	.16	16.35	2852.00	386.00	1.91	40259.00
DE	.69	51.59	1658.00	328.00	1.95	86732.00
TR	.13	9.19	724.00	317.00	2.12	7160.00
TW	2.74	100.00	354.00	183.00	1.20	60570.00
NL	.23	19.96	120.00	100.00	.76	4098.00
FR	.83	62.16	2814.00	464.00	1.90	108720.00
CH	.94	64.52	26869.00	380.00	1.35	1517800.00
IT	1.01	43.53	896.00	322.00	1.69	41276.00
JP	.99	100.00	3041.00	233.00	1.14	377743.00

Table 7.33 shows the statistics of variables responsible for the economic sustainability of HSR. The average length of the rail network for the selected HSRs is 1277km, the largest HSR network belongs to CH with the highest number of passengers and the shortest belongs to NL with the smallest number of passengers.

Table 7.33 Statistics of selected variables Group 1 (Source: Author's calculation)

	Network	**Distance**	**Time**	**Passengers**	**Productivity**	**Efficiency**
Q1	764.75	237.0	1.2375	40513.25	0.345	25.8525
Q3	2842.50	367.0	1.9075	103223.00	1.005	63.9300
Median	1277.00	319.5	1.6500	60119.50	0.885	51.2100
Max	26869.00	464.0	2.1200	1517800.00	2.740	100.0000
Min	120.00	100.0	0.7600	4098.00	0.130	9.1900

Table 7.34 shows that HSRs with the highest score in productivity and efficiency TW and JP have the shorter average distance per passenger and the shorter time on trains per passenger than 50% of the selected HSRs. However, TW and JP HSRs enter the top 50% of selected HSRs by the number of passengers in 2017. From these results conclusion can be made that HSRs that oriented on passengers that travel on average between 200-250km per journey and provided

faster journeys than average HSRs, have a higher level of productivity and efficiency.

Table 7.34 HSRs with the highest scores in selected variables from Group 1 (Source: Author's creation)

Network	Average distance per passenger	Average time in vehicle	Number of passengers	Level of Productivity	Overall Technical Efficiency
CH	FR	TR	CH	TW	JP
JP	ES	DE	JP	KR	TW
ES	CH	ES	FR	IT	CH
FR	IT	FR	DE	JP	FR
DE	DE	IT	TW	CH	DE

Table 7.35 shows the factors from Group 2 which is related to the environmental sustainability of HSR. It was not possible to investigate the relationship of OTE and Annual Electric Power Consumption for all the selected HSRs as UIC Statistics did not have data for CH.

Table 7.35 Variables related to environmental sustainability of HSRs (Source: Extract from SPSS simulation)

HSR	Electric Power Consumption Annual	Passenger-km	Average Traction Power Per Train	HS Train Sets	Total Number of Seats	Average number Seats per Train
KR	2735.00	14869.00	10800.00	109.00	67524.00	619.00
ES	2621.00	15540.00	5160.00	229.00	60063.00	262.00
DE	7969.00	28502.00	6700.00	257.00	118698.00	461.00
TR	217.00	2218.00	5050.00	13.00	5488.00	422.00
TW	443.00	11103.00	9600.00	34.00	33626.00	989.00
NL	1067.00	413.00	8800.00	26.00	9802.00	377.00
FR	6300.00	58280.00	8770.00	410.00	192813.00	470.00
CH	.00	577635.00	8960.00	2411.00	1596810.00	662.00
IT	4222.00	12997.00	7410.00	137.00	69272.00	505.00
JP	6525.00	101325.00	11500.00	398.00	376461.00	945.00

Table 7.36 shows the statistics of variables from Group 2. There is a difference in average power per train which varies from 5050kW to 11500kW. Also, there

is a large difference in the average number of seats per train with a minimum of 262 and a maximum of 989.

Table 7.36 Statistics of selected variables from Group 2 (Source: Author's calculation)

	Pass/km	Annual Power Consumption	Average Power per Train	HS Train Sets	Total Number of Seats	Average Seats per Train
Q1	11576.5	1067	6877.5	52.75	40235.25	431.75
Q3	50835.5	6300	9440.0	362.75	174284.25	651.25
Median	15204.5	2735	8785.0	183.00	68398.00	487.50
Max	577635.0	7969	11500.0	2411.00	159610.00	989.00
Min	413.0	217	5050.0	13.00	5488.00	262.00

Table 7.37 shows that the HSRs that score the highest score of Productivity and OTE (JP, TW, KR) have train sets with the highest traction power and have train sets with the largest number of seats. It is difficult to have a conclusion on total consumption of electricity as UIC Statistics do not have separate data for HSRs, only for passenger trains of all type of traction.

Table 7.37 HSRs with the highest scores in selected variables from Group 2 (Source: Author's creation)

Number of Seats	Pass/ km	Annual Power Use	Average Tr. Power per train	HS Train sets	Average Seats per Train	Level of Productivity	Overall Technical Efficiency
CH	CH	CH N/A	JP	CH	TW	TW	JP
JP	JP	FR	KR	FR	JP	KR	TW
FR	FR	JP	TW	JP	CH	IT	CH
DE	DE	IT	CH	DE	KR	JP	FR
IT	ES	KR	NL	ES	FR	CH	DE

Table 7.38 shows the factors from Group 3 which are related to the social sustainability of HSR.

Table 7.38 Variables related to social sustainability of HSRs (Source: Extract from SPSS)

HSR	Surface area of country	Population of selected country	Density of population	GDP per capita	Land taking by HSR	Mean Annual Staff Number
KR	100.30	51.50	212.00	26.15	4435.00	26352.00
ES	506.00	46.46	92.00	32.41	14260.00	14233.00
DE	357.00	80.93	227.00	46.75	8290.00	308800.00
TR	784.00	76.82	98.00	27.55	3620.00	23330.00
TW	36.20	23.70	649.00	24.29	1770.00	3222.00
NL	41.50	17.00	410.00	53.60	600.00	10845.00
FR	549.00	66.48	121.00	42.57	14070.00	136642.00
CH	9563.00	1370.84	143.00	14.94	134345.00	1841500.00
IT	301.00	60.77	202.00	34.88	4480.00	72441.00
JP	378.00	126.82	336.00	48.56	15205.00	114870.00

Table 7.39 shows the statistics of variables from Group 3. There is a difference in variables. The density of population varies between 92 inhabitants per km^2 in ES to 649 inhabitants per km^2 in TW. The population of selected countries varies from 17 million in NL to 1370.84 million in CH.

Table 7.39 Statistics of selected variables from Group 3 (Source: Author's calculation)

	Surface area of country	Population of selected country	Density of population	GDP per capita	Land taking by HSR	Mean Annual Staff
Q1	150.475	47.7200	126.50	26.500	3823.75	16507.25
Q3	538.250	79.9025	308.75	45.705	14212.50	131199.00
Median	367.500	63.6250	207.00	33.645	6385.00	49396.50
Max	9563.000	1370.8400	649.00	134345.000	134345.00	1841500.00
Min	36.200	17.0000	92.00	14.940	600.00	3222.00

Table 7.40 shows the social variables of selected countries. From Table 7.40 it can be found that HSRs that score the highest score of Productivity and OTE (JP, TW, KR) are not the largest countries in the term of surface area and population. However, the density of population is an important variable as all three HSRs from the selected group among the top 50% are with the highest density of

population. The land taken by HSR depends on how large the HSR network is and only JP is among 50% of countries with the largest land taking. As for the Annual Staff of selected operators of HSR that are involved in operation of trains DE and FR have substantially larger numbers of Annual Staff than HSRs that score the highest score of Productivity and OTE (JP, TW, KR).

Table 7.40 HSRs with the highest scores in selected variables from Group 3 (Source: Author's creation)

Surface Area of the Country	Population of Country	Density of population	GDP per Capita	Land taking by HSR	Mean Annual Staff
CH	CH	TW	NL	CH	CH
TR	JP	NL	JP	JP	DE
FR	DE	JP	DE	ES	FR
ES	TR	DE	FR	FR	JP
JP	FR	KR	DE	DE	IT

7.3.2 Scatterplot of OTE and selected variables

Before the calculated correlation, the relationship between OTE and other variables were explored. A Scatterplot was built using the SPSS software.

Figures 7.11 shows that variables "Average Distance per Passenger" and "Overall Technical Efficiency" negatively relate, the high score of Average Distance per Passenger associated with low scores of Overall Technical Efficiency.

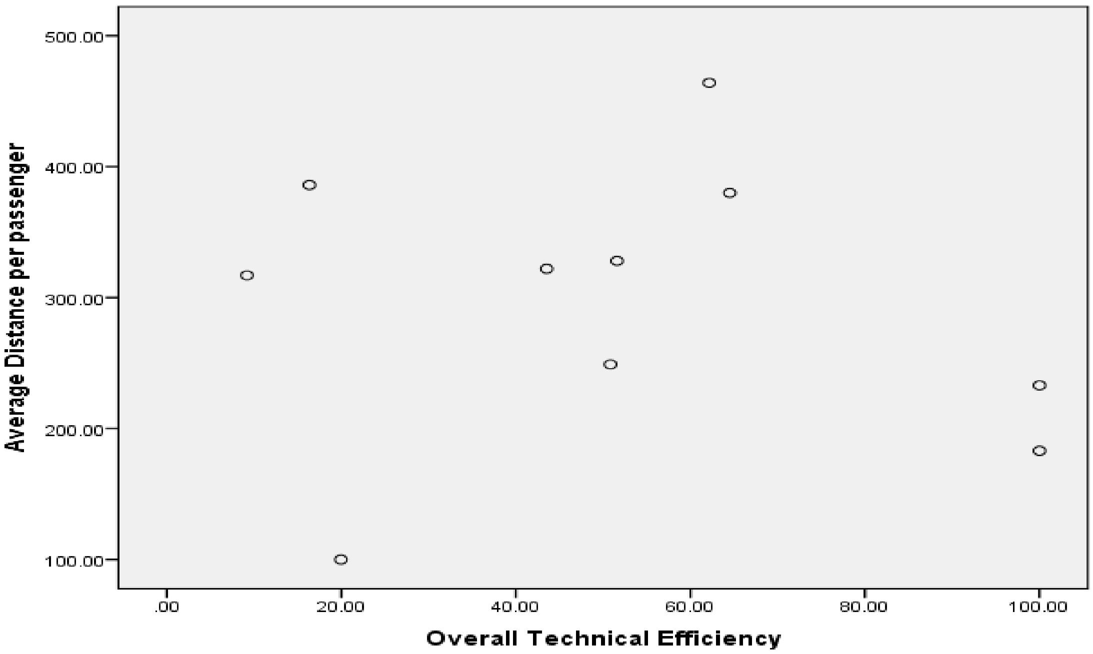

Figure 7.11 Scatterplots of two variables: average distance per passenger and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.12 shows that the length of HSR lines and overall technical efficiency do not relate.

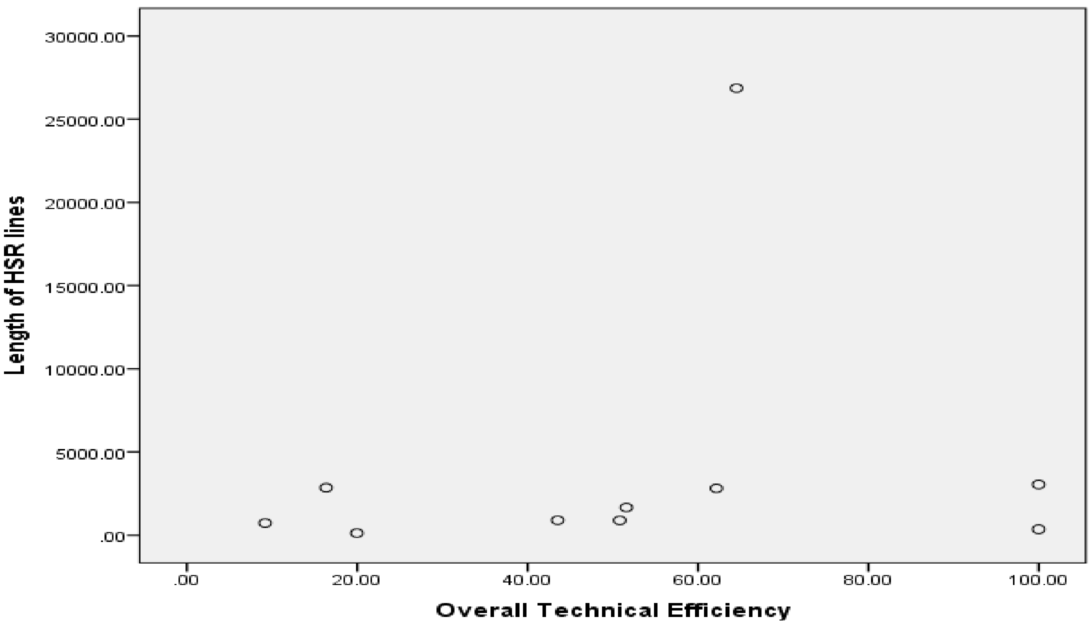

Figure 7.12 Scatterplots of two variables: length of HSRs lines and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.13 shows that the surface area of country and overall technical efficiency does not relate.

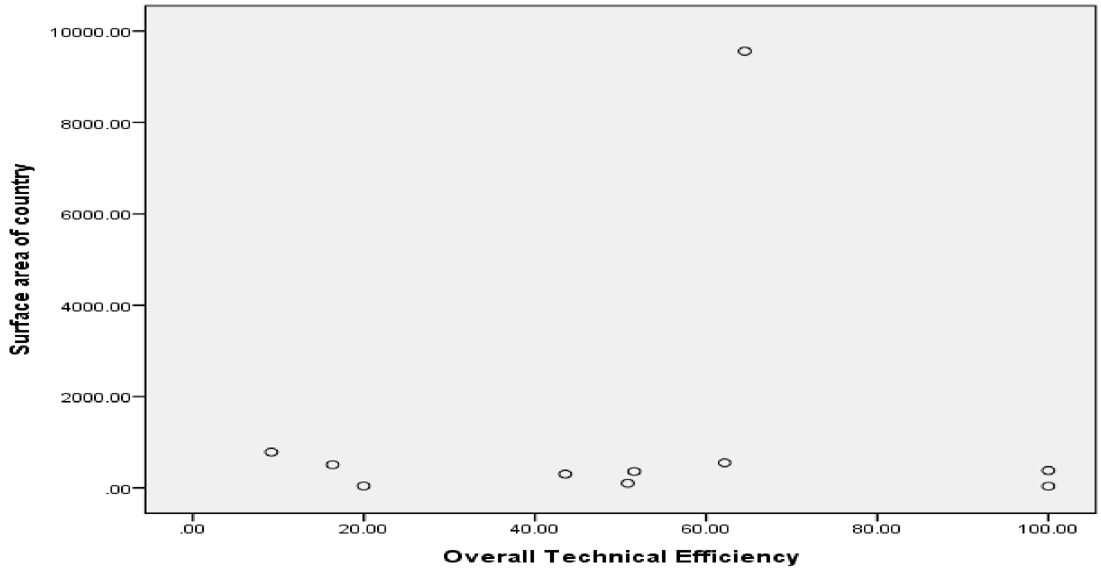

Figure 7.13 Scatterplots of two variables: surface area of countries and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.14 shows that the population of the selected country and overall technical efficiency do not relate.

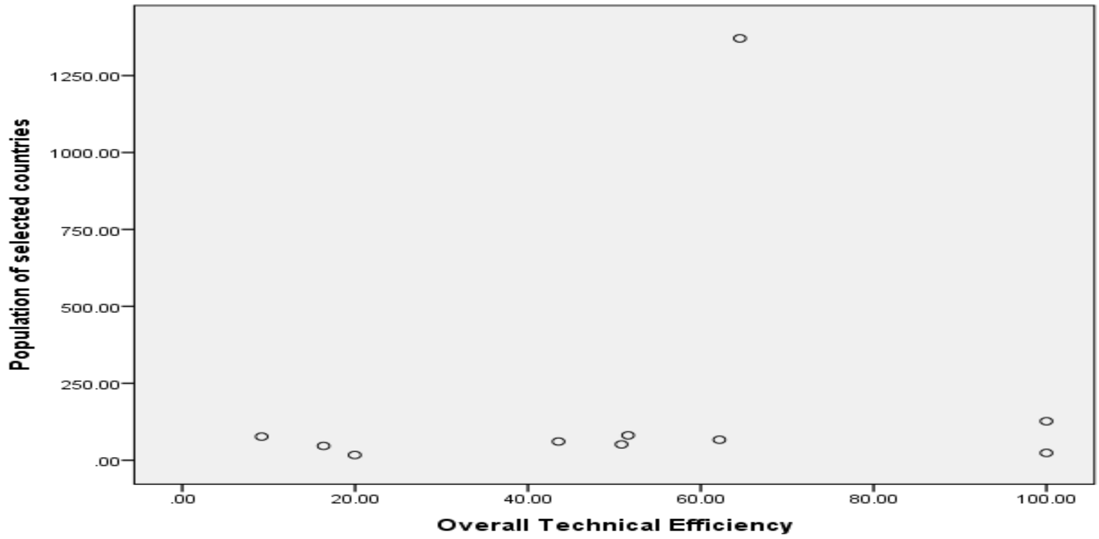

Figure 7.14 Scatterplots of two variables: population of selected countries and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.15 shows that density of population and overall technical efficiency are positively related, with increasing the density of population it increases OTE of the selected HSRs.

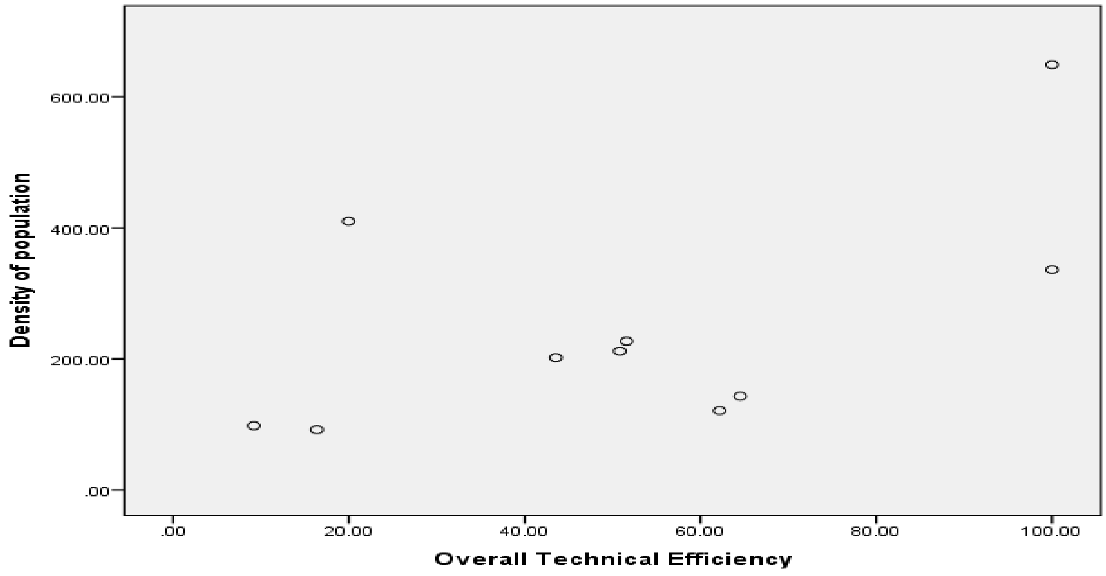

Figure 7.15 Scatterplots of two variables: density of population and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.16 shows that GDP per capita and overall technical efficiency do not relate.

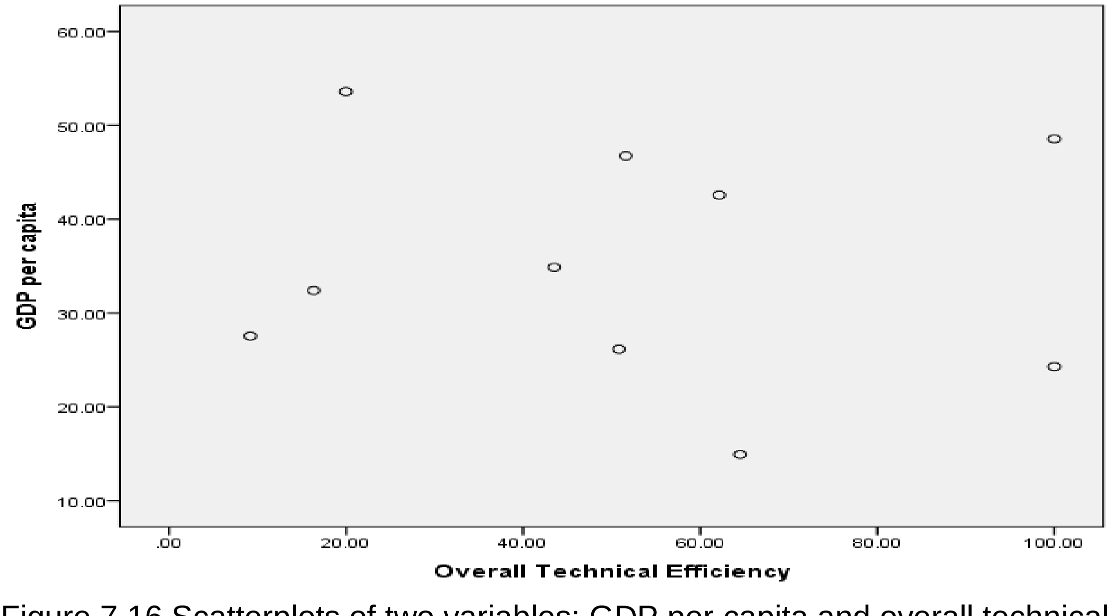

Figure 7.16 Scatterplots of two variables: GDP per capita and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.17 shows that average travel time and overall technical efficiency negatively relate, with the decreasing average travel time, OTE increases.

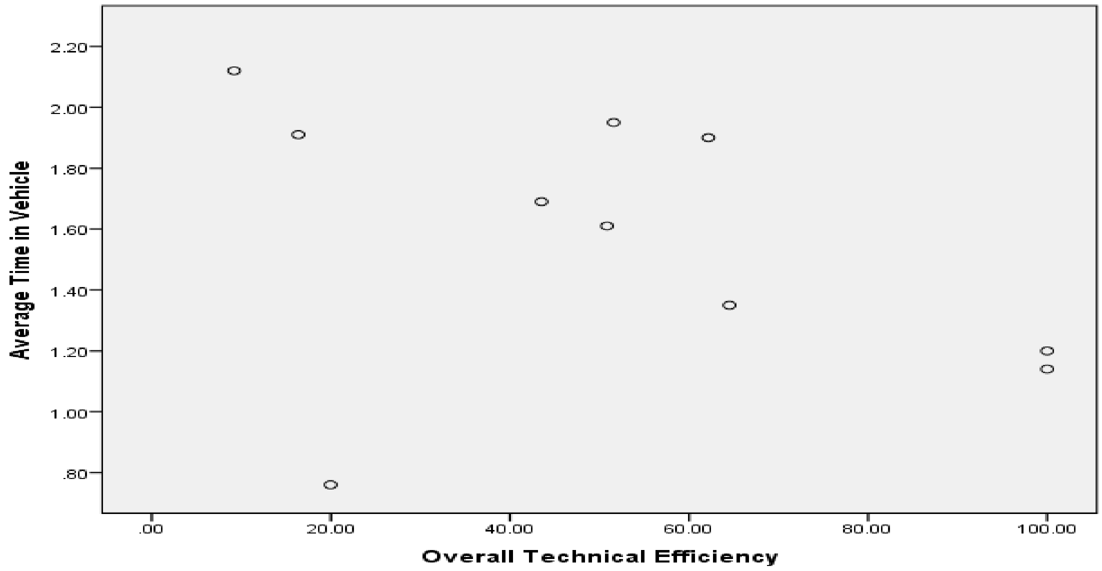

Figure 7.17 Scatterplots of two variables: average travel time and overall technical efficiency (Source: Extract from SPSS simulation)

Figure 7.18 shows that average power of EMU and overall technical efficiency are positively related, with using more powerful EMUs it increases OTE of the selected HSRs.

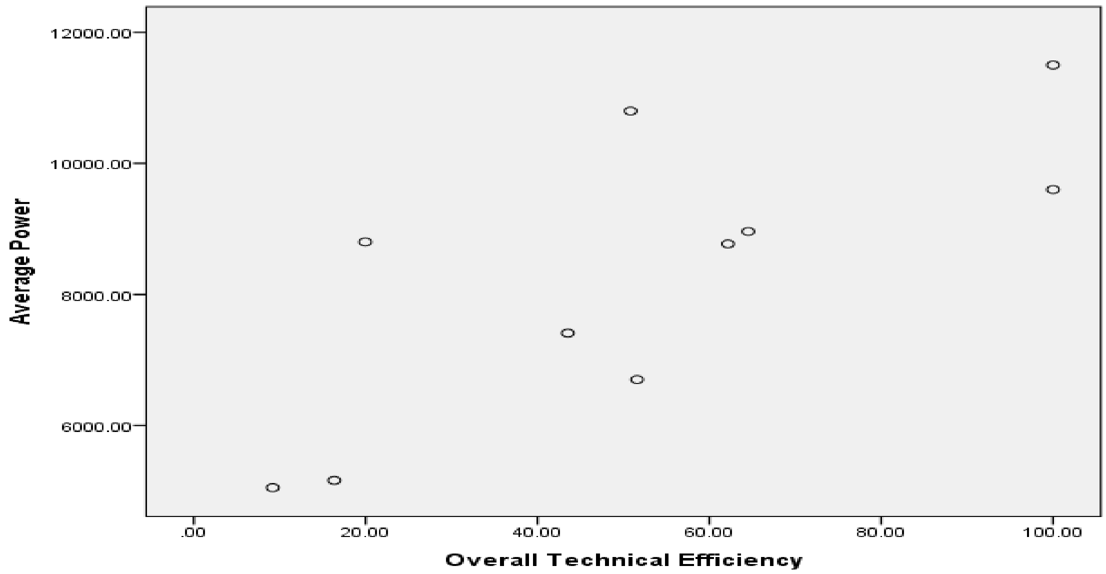

Figure 7.18 Scatterplots of two variables: average power of EMUs and overall technical efficiency (Source: Extract from SPSS simulation)

To summarise results from scatterplots of OTE and selected variables, Table 7.41 was created.

Table 7.41 Summary of exploring the relationship between selected variables and OTE (Source: Author's creation)

	Variables	Relationship	Type of Relationship
OTE	Length of HSR line	No relations	
	Surface area of country	No relations	
	Population	No relations	
	Density of population		positive
	GDP per capita	Low correlation	
	Average distance per passenger		negative
	Average time in vehicle		negative
	Average power		positive
	Land taking by HSR	No relations	
	Mean annual staff	No relations	
	Number of seats	No relations	

Table 7.41 shows that from the selected variables, two have a positive relationship and two negative relationship. The density of population and average power of employed EMUs positively related to the OTE. The average distance that passengers travel on HSR and average time on a train are negatively related to OTE.

To assess the normality of the distribution and carry out the check for outliers, the Explore option of SPSS was applied. By examining the variables there have been found one outlier CH HSR with the most extreme values in:

- Length of HSR network
- Surface area of country
- Population of country
- HS train sets
- Number of passengers
- Land taking by HSR
- Mean annual staff

Due to the fact, that there is no relationship between the above variables with productivity and OTE of HSRs, the outlier cannot affect the results of the Pearson correlation tests. If the relationship could be found between the above variables with productivity and OTE (in the case of CH HSR extreme values) it would be appropriate to use the Tobit regression.

To explore how strong the relationship is (OTE & Density of Population; OTE & Average distance travelled per passenger; OTE & Average time a passenger on a train and OTE & Average power of EMUs employed by HSRs) Pearson Correlation was applied. Selected HSRs is a small set of data. Regarding the presented Scatterplots, they have several outliers that can influence the correlation coefficient.

7.3.3 Pearson correlation test

Table 7.42 shows that the OTE has a negative relationship with two variables: Average Distance per Passenger on HSR and Average Travel Time per passenger on HSR Trains and has a positive relationship with variables such as Density of Population and Average Power of EMUs. The longer distances a passenger travels on HSRs and the longer time a passenger spends on a train the OTE of HSRs will decrease. The higher density of population in the selected country and the higher power of HSR trains, the OTE is higher.

Table 7.42 Summary of Pearson Correlation Test of the selected variables and OTE by applying IBM SPSS software (Source: Extract from SPSS)

		Density of population	Average Distance per passenger	Average Power	Average Time in Vehicle	Overall Technical Efficiency
Density of population	Pearson Correlation	1	-.777**	.502	-.712*	.565
	Sig. (2-tailed)		.008	.139	.021	.089
	N	10	10	10	10	10
Average Distance per passenger	Pearson Correlation	-.777**	1	-.407	.763*	-.121
	Sig. (2-tailed)	.008		.243	.010	.739
	N	10	10	10	10	10
Average Power	Pearson Correlation	.502	-.407	1	-.668*	.753*
	Sig. (2-tailed)	.139	.243		.035	.012
	N	10	10	10	10	10
Average Time in Vehicle	Pearson Correlation	-.712*	.763*	-.668*	1	-.391
	Sig. (2-tailed)	.021	.010	.035		.264
	N	10	10	10	10	10
Overall Technical Efficiency	Pearson Correlation	.565	-.121	.753*	-.391	1
	Sig. (2-tailed)	.089	.739	.012	.264	
	N	10	10	10	10	10

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7.43 shows that the Level of Productivity has a negative relationship with two variables: Average Distance per Passenger on HSR and Average Travel Time per passenger on HSR and has a positive relationship with variables such as Density of Population and Average Power of EMUs. The longer distances a passenger travels on HSRs and the longer time a passenger spends on a train, the productivity of HSR will decrease.

Table 7.43 Summary of Pearson Correlation Test of the selected variables and Level of Productivity of HSRs by applying SPSS software (Source: Extract from SPSS)

		Density of population	Average Distance per passenger	Average Power	Average Time in Vehicle	Level of Productivity of HSR
Density of population	Pearson Correlation	1	-.777**	.502	-.712*	.727*
	Sig. (2-tailed)		.008	.139	.021	.017
	N	10	10	10	10	10
Average Distance per passenger	Pearson Correlation	-.777**	1	-.407	.763*	-.264
	Sig. (2-tailed)	.008		.243	.010	.461
	N	10	10	10	10	10
Average Power	Pearson Correlation	.502	-.407	1	-.668*	.551
	Sig. (2-tailed)	.139	.243		.035	.099
	N	10	10	10	10	10
Average Time in Vehicle	Pearson Correlation	-.712*	.763*	-.668*	1	-.316
	Sig. (2-tailed)	.021	.010	.035		.373
	N	10	10	10	10	10
Level of Productivity of HSR	Pearson Correlation	.727*	-.264	.551	-.316	1
	Sig. (2-tailed)	.017	.461	.099	.373	
	N	10	10	10	10	10

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The higher density of population in a selected country and the higher power of HSR trains the higher productivity of the HSR. The value of the Pearson correlation coefficient can vary between -1 to +1. The value of -1 indicated perfect negative correlation, the value of +1 indicated perfect positive correlation and the correlation of 0 means that there is no relationship between variables (Pallant, 2013).

Testing the Pearson correlation coefficient has been following a guideline (Pallant, 2013) which states that the strength of the relationship is:

Small r =.10 to .29

Medium r =.30 to .49

Large r =.50 to 1.0

Table 7.44 Summary of Pearson correlation test (Source: Author’s creation)

	Variable	Pearson Correlation Coefficient	Interpretation of relationship	Percentage of variance
OTE	Density of Population	0.565	strong	31.92%
	Average distance per passenger	0.121	weak	1.46%
	Average HSR train power	0.753	strong	56.70%
	Average time on train	0.391	moderate	15.29%
Productivity	Density of Population	0.727	strong	52.85%
	Average distance per passenger	0.264	weak	6.97%
	Average HSR train power	0.551	strong	30.36%
	Average time on train	0.316	weak	9.99%

Table 7.44 shows the relationship between OTE and Productivity with selected variables. Percentage of variance shows how much variance is shared by two selected variables or how much overlap there is between two variables. The sample size is low (N=10) because the level of statistical significance has not reached statistical significance at the traditional p<.05 level.

7.4 Key findings of DEA model

Table 7.45 shows the key findings applied by the DEA model. The DEA, apart from determining the efficiency score of HSR, will find the Lambda, Peers and Target values of input and output for inefficient HSRs.

The Productivity of DMU is a ratio of produced outputs to its used inputs. Productivity represents the capability of used resources to get maximum outcomes. Technical efficiency can be responsible for travel demand by adjusting the supply scale. Technological efficiency change involves the ability of HSR to invest in new technologies, advanced IT systems and equipment. The efficiency of HSRs compared with efficiency levels of other HSRs, but not to ideal conditions. The DEA VRS model deduces that increases in inputs does unnecessary give a proportional change in the outputs and its measure of pure technical efficiency (PTE) which is not affected by scale efficiency (SE). The measure of SE shows how the size of the railway network (too large or too small) influences the Efficiency Scores of DEA CRS.

Table 7.45 Summary of key findings of the DEA model

Category	The best performers	Tendency	The worst performers	Tendency
Annual Productivity Change	KR, TW	Growth in productivity through all periods	ES, NL, TR	Through all periods experienced negative growth
Annual Technical Efficiency Change	TW	Efficient in period 2011-2017	All other selected HSR	Fluctuation in scores
Annual Technological Change	KR, TW	Positive efficiency growth through all periods	ES, TR, NL	Through all periods experienced negative growth
Efficiency Scores of DEA CRS	TW, JP	Efficiency scores over 90%	TR, ES, NL	Efficiency Scores 6-19%
Efficiency Scores of DEA VRS	JP, NL	Efficiency Scores 100%	TR, ES	Efficiency Scores 7-19%
Scale Efficiency Scores	TW, KR	Efficiency scores over 98%	NL, CH	Efficiency Scores 19-55%

7.5 Key factors affecting the sustainability of the HSR

The results show four key factors that have the highest influence on the sustainability of HSRs, and they are:

- **Density of population**
- **Average HSR trains' traction power**
- **Average time that passengers spend on a train**
- **Average distance per passenger**

These factors are now explained in detail.

Density of population:

This research found that the density of population has a strong positive relationship with productivity and efficiency of HSRs. This is an important finding as it influences decisions on investments in the future development of HSRs. The HSRs can be very successful where they are needed to transport thousands of people every day. The density of population is an important variable, as all three of the best performing HSRs (TW, JP, KR) are among the top 50% with the highest density of population.

The projection in population changes can influence decision-makers to refrain from expanding the HSRs. One of the examples of this can be Japan, where the future decline in Japan's population from the current 127 million to 105 million by 2045. There will be a slowdown in new developments of HSR, as there will not be enough demand. However, not always, economic benefits or environmental awareness can enhance the development of HSRs.

Average HSR trains' traction power:

According to this factor, there is a strong relationship between average HS trains' traction power and productivity and efficiency of HSRs. On average, trains in Asia have higher traction power than in Europe. This is due to several factors' technical characteristics of RS, train formation and the number of stops. Trains can have different formations; 16 cars as have Shinkansen Series 500 and Shinkansen Series 700 in Japan or eight cars that Frecciarossa has in Italy. Trains in Asia approximately have on average twice the capacity than trains in Europe. Table 7.29 shows that the HSRs that score the highest score of Productivity and OTE (JP, TW, KR) have train sets with the highest traction power and have train sets with the largest number of seats.

Also, the lowest energy consumption (kWt/seat-km) belongs to the Shinkansen trains (Figure 5.6). The energy consumption is less, but the average speed is higher. The explanation of this can be that in Japan, rolling stock is renewed to a more efficient every 15-20 years. Newer HSRS have an improved design, more energy efficient. In Europe trains are designed for 30-40 years of service life.

Average time that passengers spend on a train:

It has been found that the average time that passengers spend on a train and the productivity and technical efficiency of HSRs have a negative relationship. This means that with increasing the time that passengers spend on trains, the productivity and technical efficiency of HSRs decreases. The higher the speed of a train the less time passengers spend on the train. Also, trains that run faster reduce the journey time, reduce the emissions in the corridor and increase the capacity of the line. These will support the sustainability of HSRs.

Average distance per passenger:

The average distance that passengers travel on HS trains is negatively linked to the productivity and technical efficiency of HSRs. This means that increasing the distance that passengers travel decreases the productivity and technical efficiency of HSRs. The HSR services that oriented on median distance services between 200-250km are more productive and efficient than short or long-distance services. Table 7.26 shows that HSRs with the highest score in productivity and efficiency TW and JP have the shorter average distance per passenger and a shorter time on trains per passenger than 50% of the selected HSRs.

However, TW and JP HSRs enter the top 50% of selected HSRs by the number of passengers in 2017. From these results conclusions can be made that HSRs that oriented on passengers that travel on average between 200-250km per journey and provide faster journeys than average HSRs, have a higher level of productivity and efficiency.

7.6 Conclusions

In this research, two DEA models CCR and BCC were employed to investigate the selected ten HSRs for the period 2010-2017 and find the best performer, and to look for ways to maximise HSR productivity and efficiency. The KR and TW HSRs were found to be the best performers and have grown in productivity throughout the whole period. Regarding the Technical Efficiency Change, results show that there is no HSRs efficient through the full period. The TW HSR is the best in the selected group in using the railway network to provide the achieved number of passengers and passenger-km.

Regarding the OTE scores, TW HSR is the best performer with a score of 95.63%. Regarding PTE, the results show that the PTE of the selected HSRs in the period 2010-2017 decreases. Between two regions, Europe, and Asia, the HSRs in Asia show higher productivity and efficiency scores. It was found that four factors have the strongest influence on the sustainability of HSR. They are, density of population, average HSR trains' traction power, average time that passengers spend on a train and average distance per passenger.

Chapter 8

Discussion and Critical Evaluation of the Results

8.1 Introduction

Productivity and efficiency characterise the performance of HSRs, and it needs to look at ways to increase them. From a regulators' point of view inefficient HSRs will need subsidies from the governments, but the efficient HSR positively influences the growth of economy in an area. From the stakeholders' point of view, only efficient HSRs will return resources that was invested in its development. From the customers' point of view, only efficient HSRs can provide a high level of service.

8.2 Changes in productivity and efficiency scores of the selected HSRs

Regarding the changes in productivity scores, the present research found that selected HSRs can be divided into three groups. The first group (ES, TR, NL) of HSRs has the negative growth in productivity, the second group (FR, CH, IT, JP, DE) productivity growth fluctuates around 1 and the third group (KR, TW) has productivity growth substantially higher than 1. Only one HSR, TW has a visible increase in productivity, which consistently increases from 2011 to 2017. From 2013, KR HSR has a sharp decrease in productivity; nevertheless, its productivity is still higher than for most HSRs.

The Annual Technical Efficiency Change reflects the level of resource usage. The results of the DEA show that the Annual Technical Efficiency Change scores of the selected HSRs from 2010 to 2014 decrease. This can be explained by the slowdown of the global economy after the crisis in 2008. However, from 2014 there was a noticeable improvement in efficiency scores for two years with another round of decrease from 2016. It can be a sign of another round in the slowdown of a global economy and another round of recession. In 2016-2017 five HSRs have negative growth in Annual Technical Efficiency Change (KR, ES, DE, FR, CH), three HSRs have growth (TR,NL, IT) and two HSR (TW and JP) have the technical efficiency change equal 1 that means no changes to the previous period.

Regarding the Annual Technological Efficiency Change all selected HSRs can be divided into three groups The first group (ES, TR, NL) has technological changes in the negative area, the second group (DE, FR, CH) changes fluctuating around 1 and in the third group (KR, TW) changes are observed between 1,5 and 2.74. Two HSRs KR and TW experienced efficiency growth. The technological efficiency change implies the ability of HSR to invest in new technologies, advanced IT systems and equipment. The two HSRs that have the highest score in Annual Technological Change were launched for service in the last 15 years. They have the highest and the most advanced technologies worldwide. The problems of ES and TR are too big a network and not enough revenue to continuously update their network. The DE, FR, and CH HSRs have a stable position. They do not show any improvements or any deterioration.

Regarding to Overall Technical Efficiency in the selected period of 2010-2017 no HSR was efficient throughout the whole period. From 2010 to 2017 the TW, CH, JP and TR HSRs increased their score of OTE, and FR, KR, ES, DE, FR and NL HSRs decreased their score of OTE. The KR HSR was efficient from 2010 to 2014 and from 2015 to 2017 TW HSR was efficient. All other selected HSRs have a fluctuation in Technical Efficiency scores. It means that there are opportunities to increase outputs without increasing inputs.

In 2017, the TW and JP railways were found to be the most efficient amongst the ten HSRs taking into consideration maximum peer count, seven for each HSR. These two HSRs can be considered benchmarks for the rest of the selected HSRs. The HSRs may need to consider improving managerial principles and techniques to optimise utilization of their HSR network. Notable improvements can be made if the OTE of selected HSRs are increased. The differences in OTE between HSRs is mostly related to levels in PTE.

The results of OTE analysis indicate that there is a substantial opportunity of HSRs in improvement in OTE. The PTE and SE scores show that HSRs in Europe had lower efficiency scores than HSRs in Asia in the selected period 2010-2017. The highest mean of the Pure Technical Efficiency score was for TW and JP and the lowest for TR with 0.0732. These results show that TR used an inappropriate size of their resources to provide services to their number of customers and their ridership was too low for the existing HSR network. The mean PTE and SE scores for all selected HSRs between 2010 and 2017 are 0.6885 and 0.9062, respectively. The SE contributes more to OTE compared to PTE.

The OTE scores for HSRs varies from 6.78% for TR to 95.63% for TW. The TR HSR must increase their number of passengers by 93.22% to be efficient and TW needs to increase the number of passengers by 4.37%. CH HSR has the largest HSR network but average performance for the selected period is only 55.08% and needs to increase their number of passengers by 44.92% to be efficient. This can be partially explained by the introduction of another 6300km HSR lines in the last years and it will take some time to be fully developed. To rank the HSRs for the entire period according to their average score, the TW HSR is the best followed by JP, KR, DE, FR, CH, IT, NL, ES, TR.

The selected HSRs have a large difference of their railway networks and to measure the Pure Technical Efficiency which is not affected by Scale Efficiency the DEA VRS model was applied. The results show that the PTE of the selected HSRs in the period 2010-2017 decreases. Only two HSRs NL and JP were recorded as fully efficient throughout the whole observed period. For them, OTE was not caused by poor inputs utilization but by the operation of HSR with an inappropriate scale size.

To minimize costs and maximise revenue, HSRs should operate at their most productive scale size. Application of Returns-to-Scale (RTS) helps to find how the size of scale will influence the productivity. The scale inefficiency is observed if the RTS can take two forms: increasing returns-to-scale or decreasing returns-to-scale. Increasing RTS means that HSRs can gain efficiency by increasing outputs and decreasing RTS means that a reduction in the scale of HSR increases efficiency. An HSR is scale efficient if it operates at Constant Return-to-Scale (CRS). The two HSRs (TW and JP) have CRS, so they are scale efficient. The IRS is a predominate form of scale inefficiency in selected HSRs. The seven HSRs have IRS and by increasing the output will improve the OTE, they are KR, ES, DE, TR, NL, FR, IT, but the CH HSR needs to reduce in scale to achieve efficiency.

The reason for the low score in Europe was the increase in competition between different transportation modes, particularly with low-cost airlines and coaches.

The reason for the low score in Asia can be that HSR network is not fully established, as in China for example it started operation from 2010, in Taiwan from 2007. For this analysis, the NL HSR has not been included in the Europe region as input data for NL HSR looks doubtful and UIC Statistics suggested not to take it into consideration.

The DEA method identified relatively poor performance of some HSRs from the selected group. The DEA method measured input and output slacks for inefficient HSRs and gave each HSR targets to improve efficiency. The downside of using the DEA approach to benchmark HSRs in the selected group is that the DEA method does not investigate cases of poor efficiency. The results and interpretation of the DEA method depend on the model specification and on selected input and output variables.

8.3 Results of IBM SPSS analysis

To further investigate the difference in HSRs performance the IBM SPSS software has been applied. The results of IBM SPSS show that the strongest relationship of OTE and Productivity have to Density of Population and Average Traction Power of Train and the weakest relationship to Average Distance per Passenger and Average Time on Train.

Before calculating the correlation, the relation between continuous variables is explored by generating a scatterplot. The scatterplot shows that it is a linear or curvilinear relation of selected variables. As in this research a linear relationship has been observed it is suitable for correlation analysis. The regression analysis presumes there are two types of variables, dependent variable (length of HSR network, surface area of country, population of country, HS train sets, number of passengers, land taking by HSR, mean annual staff, density of population, average distance per passenger, average time in a vehicle, average traction power) and independent variables (productivity and OTE). To investigate the relationship between these variables, the Pearson correlation analysis has been applied.

The results of the Pearson correlation analysis show that from the selected variables, two have a positive relationship and two have a negative relationship. The density of population and average power of employed EMUs is positively related to productivity. The average distance that passengers travel on HSR and average time on a train is negatively related to OTE. The correlation is significant at 95% confidence interval.

Depending on the current research, some suggestions can be made on measures to improve the sustainability of HSRs. The most profitable and efficient are railways in countries with a higher density of population, also it is an important quality and capacity of RS. Results of research show that the HSRs that have the highest score of productivity and OTE (JP, TW, KR) have train sets with the highest traction power and have train sets with the largest number of seats. This allows the operator to reduce travel time and increase the capacity of lines and revenues.

Also, the results of present research show that HSRs with the highest score in productivity and efficiency TW and JP have the shorter average distance per passenger and a shorter time on trains per passenger than 50% of selected HSRs. The TW and JP HSRs enter the top 50% of selected HSRs by the number of passengers in 2017. From these results a conclusion can be made that HSRs that oriented on passengers that travel on average between 200-250km per journey and provided faster journeys than average HSRs, have a higher level of productivity and efficiency. From this conclusion, another assumption follows that the location of railway stations can influence the sustainability of HSRs.

The HSRs that score the highest score of productivity and OTE (JP, TW, KR) are not the largest countries in the term of surface area and population. However, the density of population is an important variable as all three HSRs from the selected group are among the top 50% with the highest density of population. The land taken by HSR depends on how large the HSR network is and only JP is among 50% of countries with the largest land taken. The DE and FR HSRs have substantially more staff involved in operation than HSRs that have the highest score of productivity and OTE (JP, TW, KR). The number of staff is one of the indicators of efficiency of any company.

8.4 Conclusions

This research evaluates the efficiency of HSRs worldwide individually for the selected period 2010-2017, also HSRs are grouped into three groups as HSRs in Europe, HSRs in Asia and all HSRs. It was found that OTE for HSRs in Europe was between 0.3656 and 0.5472 and for HSRs in Asia between 0.7884 and 0.8744. The mean TE for HSRs in Europe is 0.4413, and this indicated that HSRs can serve the same number of passengers with 55.87% less input. The HSRs in Asia performs with a higher level of efficiency than in Europe. It can be explained by the higher capacity of trains as they are almost twice the size than in Europe and the higher speeds of HS trains.

Chapter 9

Conclusions and Recommendations for Future Work

9.1 Introduction

The modern world has many transport problems, but also a wide variety of initiatives and solutions. One solution should be the HSR. HSR contributes to congestion reduction and as a result a reduction of air and water pollution. HSR transport is the most energy efficient mode of transportation and is continuously improving performance in terms of energy use per passenger-kilometre.

Resource efficiency for HSR means there is a need to minimize emissions from the railway infrastructure construction and to increase recyclability of train components and parts of infrastructure. Reduction of the weight of rolling stock will reduce the amount of raw materials used for production. Profitability of newly constructed HSRs heavily depends on the expected volume of demand, but demand depends on the willing-to-pay and density of the population.

To improve the HSRs efficiency on an international competitive basis, it is important to develop tools to compare different HSRs systems. Benchmarking is a popular approach to measuring the performance of selected HSRs against each other.

9.2 How the research outcomes met the research questions and objectives

The aim of this study is to evaluate the sustainability of selected HSRs and to identify factors that affect such sustainability.

The objectives of this research are:

- To evaluate productivity, technical and technological efficiency of the selected HSRs
- To define the factors that can affect productivity and efficiency scores
- To make suggestions for improving the sustainability of HSRs.

To fulfil this, a three-stage approach has been used. In the first stage, qualitative data is analysed by applying the NVivo software. In the second stage, MI DEA software is employed whilst the IBM SPSS software is used in the final stage.

In the first stage, ten selected HSRs are studied and their performance and factors that influence their sustainability are investigated. In the second stage, the analysis is carried out using PIM-DEAsoft-V3.0 mainly to find the technical efficiency, pure technical efficiency, and scale efficiencies for individual HSRs.

To understand the performance of HSRs, cross-section data from UIC Statistics and World Bank websites have been used. This study selected one input variable length of the HSR network and two output variables, namely, train-km and passenger-km. The results of output-oriented DEAs with constant and variable returns to scale have identified the best performers among the ten HSRs. DEAs classify HSRs into two groups: efficient and inefficient by comparing input-output data of selected HSRs.

The MI DEA is employed as it is important to investigate the performance of selected HSRs for several years for which it provides the ability to avoid concentration on a single year which can be affected by factors not related to efficiency. The MI DEA application produced the productivity ratio, which is the outputs produced to inputs consumed. The SPSS analysis is used in the final stage to find the relationship between the overall technical efficiency and productivity with factors that affect sustainability.

To select the factors that can affect sustainability of HSRs, several related publications and research findings were thoroughly studied. Research is limited by available data. Selected factors are combined into three groups and each group is investigated by applying Scatterplot and the Pearson Correlation Test using IBM SPSS software.

The results were presented in three sections. Firstly, descriptive statistics on the technical qualities of selected HSRs and three pillars of sustainability are presented. Secondly, the application of MI DEA software to benchmark the selected HSRs is then followed by discussion and analysis of the obtained results. Finally, the most influential factors in terms of HSR sustainability among the identified key factors are defined.

This project has found that the average efficiency score for all HSRs for Constant Return to Scale (CRS) model is 57.24% and for Variable Return to Scale (VRS) model is 72.01%. The Technical Efficiency Change shows that there is no HSRs efficient through the full period 2010-2017. The TW HSR is efficient during the period 2011-2017. The TW HSR is the best in the selected group in using the railway network to provide the achieved number of passengers and passenger-km. The rest of the selected HSRs can increase passengers and passenger-km without the need to increase the length of the railway network.

When estimating the productivity three groups of HSRs can be distinguished. The first group (ES, TR, NL) has a negative growth in productivity whilst in the second group (FR, CH, IT, JP, DE) the productivity growth fluctuates around 1 and the third group (KR, TW) has productivity growth substantially higher than 1. Only two HSRs, KR and TW have growth in productivity through all periods of 2010-2017, but only one HSR, TW, has a continuous and consistent increase in productivity between 2011 to 2017. The productivity of DE has grown between 2011 to 2016 and dropped in 2017. The productivity of ES, NL and TR through all periods experienced negative growth.

In the case of Technological Change, KR and TW HSRs have experienced positive efficiency growth, but ES, TR and NL experienced a negative efficiency through the selected period. In the period 2010-2013 FR, CH and IT HSRs have positive efficiency growth and a negative growth in period 2014-2017.

Regarding the Overall Technical Efficiency (OTE), the average score for all selected HSRs in period 2010-2017 is 57.24%. The highest score is of TW HSR which is 95.63% and the lowest score is of TR at 6.78%. Therefore ranking the HSRs for the entire period according to their average score of OTE shows that the best is TW HSR operator followed by JP, KR, DE, FR, CH, IT, NL, ES, TR. Inefficient HSRs can improve their efficiency by increasing the outputs.

The highest mean Scale Efficiency score is recorded for TW and the lowest score was NL and CH. The results show that CH used an inappropriate size of their sources. The mean Pure Technical Efficiency and SE of all the HSRs over the selected period is 72.01% and 83.47% respectively. Regarding the PTE, only two HSRs namely, NL and JP are recorded as fully efficient through the whole observed period. The rest of selected HSRs have decreased PTE. For 2017, two HSRs are efficient, but to understand which of them perform better, the observation of Peers frequency can be used. The HSR that Peers mostly is the best performer from the two. In the case of 2017, it is the JP HSR.

The results show that OTE and productivity of the selected HSRs have a strong relationship with the density of population in their countries and with the average traction power of trains in the selected HSRs. HSR has a higher OTE and productivity if it is in a country that has a higher density of population and uses more powerful trains.

The average time that passengers spend on an HSR has a negative moderate relationship with OTE and productivity. That means when passengers spend more time on a train the OTE and productivity of selected HSRs decrease. Also, it was found that the Average Distance per passenger travelling by HSRs has a negative weak relationship with OTE and productivity of HSRs. When the distance that a passenger travels by HSR increases the OTE and productivity decreases. The results also point that some variables such as the length of HSR, surface area of country, population, and GDP per Capita do not have a relationship with OTE and productivity of the HSRs.

The OTE calculated under CRS by solving CCR DEA model shows that the OTE score of all HSRs for the selected period of 2010-2017 is 0.6227, which shows that HSRs need to have 37.73% more of output in order to have the same amount of input. In Europe, the highest score of OTE is 0.5472 compared with 0.8744 in Asia. The lowest score for the HSRs in Europe is 0.3656 whilst in Asia such score is 0.7884.

This study has identified the most influential factors that affect the sustainability of HSRs. These are, the Density of Population, Traction Power of RS, Average Distance per Passenger and Average Time on Train. Due to the lack of data, other factors related to the geographic regions, and the environment could not be evaluated in this research.

9.3 Contribution of this research leads to a wider knowledge in the sustainability of HSRs

A major difference between the study reported in the thesis and other works is the fact that this project proposes a new methodology for the assessment of HSRs sustainability and the identification of the key factors affecting the sustainability. A three-stage approach is applied which employs NVivo, MI DEA and IBM SPSS to benchmark and evaluate the performance of the selected HSRs and to find factors that have the highest influence on their sustainability. This study has explored several numbers of key variables that are not evaluated before, such as the average distance per passenger, average time in a vehicle, average traction power per train and land taking by HSR. There is a correlation of variables with the OTE and productivity of the selected HSRs.

This study has found that the Asian HSRs perform better than HSRs in Europe. The best performing HSRs (JP, KR, TW) have one feature in common that they all have the same development strategy-dedicated HSR line to serve a 500-600km long corridor which links two megacities in less than three hours. Also, from this study it can be concluded that there are two more mandatory conditions to have an efficient HSR system as macro-economic factors influence demand for output. There conditions are that there must be a high density of population and that the HSR stations are served by a wide public transport system.

In contrast to the dedicated corridor model (JP, KR, TW), in Europe there is a hybrid radial network model (DE, IT, FR HSRs). The radial network connects the capital of a country with major urban areas and with few intermediate stations. This model implies that HS trains and conventional trains that use the same branch lines or have fully mixed traffic as in DE. This model allows increases in the number of stations served by the HS trains. In the case of CH and ES HSRs, the HSR lines widely cover countries linking megapolises and medium-size cities. Results of this research show that HSRs with a hybrid radial network are less productive and less efficient.

9.4 Contribution of this research to the practice of developing and operating HSRs

The results of this study can help make decisions to identify future HSR projects that will potentially have high OTE and productivity. This research found that the density of population has a strong positive relationship with productivity and efficiency of HSRs. This study has identified the factors that influence the performance of HSRs. The density of population and the projection in population changes are among the most important factors that underline the decision in the development of HSR systems by decision-makers. There is a strong relationship between the average HS trains' traction power and the productivity and the efficiency of HSRs. HSRs have higher productivity and efficiency scores if operators employ HSRS with higher traction power. Trains have a higher speed and HSR lines have higher capacity and reduced passenger travel time.

This research found that among the ten investigated HSRs which are oriented on median distance services between 200-250km and provide faster journeys are more productive and efficient than the rest of HSRs. This finding can be taken into consideration when choosing the location of railway stations along the railway corridor. The location of stations will have a huge influence on the performance of railway networks and will also have a high impact on costs and returns of the HSR corridor and sustainable whole life approach.

However, there is a need for future work to expand some other variables. Dataset used in this study lacks some variables such as the number of accidents, CO_2 emissions produced by selected HSRs and the number of vehicles in selected countries which can be useful in analysing the performance of HSRs.

Further work can extend this current research in various directions. First, to expand the number of the analysed HSRs to include all the sixteen existing HSRs. Second, to expand the number of inputs and output variables. Including extra variables, for a better evaluation and understanding of the performance of selected HSRs. However, this will depend on the availability of reliable data. Third, the analysis can be on a wider level including all HSR operators, not only at the country level.

REFERENCES

About-france.com. (2019). [online] Available at: http://about-france.com/tourism/main-towns-cities.htm [Accessed 14 Aug. 2019].

Agarwal, G. (2011). *High Speed Rail Technology*. [online] Academia.edu. Available at: https://www.academia.edu/6395790/High_Speed_Rail_Technology [Accessed 12 Jul. 2017].

Ahmad, M., Ishtiaq, M., Hamid, K., Usman Khurram, M. and Nawaz, A. (2017). Data Envelopment Analysis and Tobit Analysis for Firm Efficiency in Perspective of Working Capital Management in Manufacturing Sector of Pakistan. *SSRN Electronic Journal*. [online] Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2911577 [Accessed 12 Oct. 2019].

Akkoc, R. (2016) *German train crash: 'At least ten' killed and 150 injured in Bavaria*. Available at: http://www.telegraph.co.uk/news/worldnews/europe/germany/12147601/German-train-crash-Several-killed-and-100-injured-in-Bad-Aibling-Bavaria-live.html [Accessed 12 January 2017].

Ali, A., T. (2014) *Railway Engineering and Maintenance*, Lecture Notes, Department of Civil Engineering, Faculty of Engineering, Science and the Built Environment, London South Bank University, London, UK.

Alin, J., Batta, R., Baum, T., Bricker, K., Dodds, R., Durbarry, R., Farsari, I., George, C., Gössling, S., Lohmann, G., Moura, A.K., Hassanal, A., Bin, B., Bagul, P., Peeters, P., Rath, J., Scott, D., Spenceley, A., Stanford, D., Twining-Ward, L. and Wild, C. (2011) *Peter Prokosch*. Available at: http://www.unep.org/resourceefficiency/Portals/24147/scp/business/tourism/greeneconomy_tourism.pdf [Accessed 23 October 2016].

Amiril, A., Nawawi, A., Takim, R. and Latif, S. (2014). Transportation Infrastructure Project Sustainability Factors and Performance. *Procedia - Social and Behavioral Sciences*, [online] 153, pp.90-98. Available at: https://www.sciencedirect.com/science/article/pii/S187704281405486X [Accessed 23 Nov. 2019].

Amirteimoori, A., Kordrostami, S. and Sarparast, M. (2006). Modeling undesirable factors in data envelopment analysis. *Applied Mathematics and Computation*, [online] 180(2), pp.444-452. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0096300306000075 [Accessed 6 Aug. 2019].

Amos, P., Bullock, D. and Sondhi, J. (2010) *High-speed rail: The fast track to economic development? (English)*. Available at: http://documents.worldbank.org/curated/en/2010/07/12582340/high-speed-rail-fast-track-economic-development [Accessed 12 January 2017].

Andersen, P. and Petersen, N. (1993). A Procedure for Ranking Efficient Units in Data Envelopment Analysis. *Management Science*, [online] 39(10), pp.1261-1264. Available at: https://pubsonline.informs.org/doi/abs/10.1287/mnsc.39.10.1261 [Accessed 6 Aug. 2019].

Andries, V. (2016). *The Recyclable Train – By Véronique Andriès, Alstom*. [online] Railway News. Available at: https://railway-news.com/the-recyclable-train/ [Accessed 12 Jul. 2017].

Angeles, L., Francisco, S., Madrid, B.C., Zhong, Bel, G. and Warner, M.E. (2014) *High-speed rail accessibility: A comparative analysis of urban access in*. Available at: http://tudelft.nl/fileadmin/Faculteit/TBM/Onderzoek/EJTIR/Back_issues/14.4/2014_04_09.pdf [Accessed 23 October 2016].

Angulo-Meza, L. and Lins, M. (2002). Review of Methods for Increasing Discrimination in Data Envelopment Analysis. *Annals of Operations Research*, [online] 116(1/4), pp.225-242. Available at: https://link.springer.com/article/10.1023%2FA%3A1021340616758 [Accessed 14 April 2019].

Archive.ipcc.ch. (2019). *Projections of Future Changes in Climate - AR4 WGI Summary for Policymakers*. [online] Available at: https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html [Accessed 3 August 2019].

Assets.publishing.service.gov.uk. (2019b). [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/552492/rail-freight-strategy.pdf [Accessed 13 Aug. 2019].

Assets.publishing.service.gov.uk. (2019c). [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/811031/hs2-phase-2a-statement-of-reasons-print.pdf [Accessed 14 Aug. 2019].

Avkiran, N. (2001). Investigating technical and scale efficiencies of Australian Universities through data envelopment analysis. *Socio-Economic Planning Sciences*, [online] 35(1), pp.57-80. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0038012100000100?via%3Dihub [Accessed 12 Dec. 2019].

Azadeh, A., Ghaderi, S. and Izadbakhsh, H. (2008). Integration of DEA and AHP with computer simulation for railway system improvement and optimization. *Applied Mathematics and Computation*, [online] 195(2), pp.775-785. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0096300307006170 [Accessed 6 Aug. 2019].

Banister, D. (2000). *European transport policy and sustainable mobility*. London: Spon Press, pp. 22, 78.

Banister, D. (2005) *Unsustainable transport: city transport in the new century*, London Routledge c/o Taylor & Francis, pp. 1, 14, 22, 62.

Baron, T. (2009) "High Speed Rail Contribution to Sustainable Mobility". Available from www.docplayer.fr/3506286-high-speed-rail-contribution [Accessed 7 April 2016].

Barros, C. and Perrigot, R., 2020. *Franchised Network Efficiency: A DEA Application To US Networks*. [online] Available at: <https://link.springer.com/chapter/10.1007%2F978-3-7908-1758-4_10> [Accessed 4 April 2020].

Batterbury, Si. (2007) *High-speed rail: A catalyst for sustainable city development: Sustainable cities network*. Available at:

http://www.sustainablecitiesnet.com/research/high-speed-rail-a-catalyst-for-sustainable-city-development/ [Accessed 23 October 2016].

Bi, G., Song, W. and Wu, J. (2014). A clustering method for evaluating the environmental performance based on slacks-based measure. *Computers & Industrial Engineering*, [online] 72, pp.169-177. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360835214000898 [Accessed 6 Aug. 2019].

Blackmore, N. (2014) *Want to live close to a station? That'll be an extra £42, 000*. Available at: http://www.telegraph.co.uk/finance/property/house-prices/11062928/Want-to-live-close-to-a-station-Thatll-be-an-extra-42000.html (Accessed 23 October 2016).

Bodman, A. (2019). *Debts and subsidies for High Speed Rail*. [online] STOP HS2 - The national campaign against High Speed Rail 2 - HS2 - No business case, No environmental case, No money to pay for it. Available at: http://stophs2.org/news/5712-debts-subsidies-high-speed-rail [Accessed 8 Aug. 2019].

Bombardier Transportation. (2019). *High-speed*. [online] Available at: http://www.bombardier.com/en/transportation/products-services/rail-vehicles/high-speed-trains/zefiro.html [Accessed 3 August 2019].

Boyd, G. and Pang, J. (2000). Estimating the linkage between energy efficiency and productivity. *Energy Policy*, [online] 28(5), pp.289-296. Available at: https://www.sciencedirect.com/science/article/pii/S0301421500000161 [Accessed 6 Aug. 2019].

Bradsher, K. (2019). *Taiwan's Bullet Trains Can't Outrun Controversy*. [online] Nytimes.com. Available at: https://www.nytimes.com/2007/01/04/world/asia/04taipei.html [Accessed 23 Oct. 2019].

Bray, S., Caggiani, L. and Ottomanelli, M. (2015). Measuring Transport Systems Efficiency Under Uncertainty by Fuzzy Sets Theory Based Data Envelopment Analysis: Theoretical and Practical Comparison with Traditional DEA Model. *Transportation Research Procedia*, [online] 5, pp.186-200. Available at:

https://www.sciencedirect.com/science/article/pii/S235214651500006X [Accessed 10 Oct. 2019].

Briginshaw, D. (2017). *New line-up in top 10 rolling stock builders*. [online] Railjournal.com. Available at: http://www.railjournal.com/index.php/rolling-stock/new-line-up-in-top-10-rolling-stock-builders.html [Accessed 13 July 2017].

Brunello, L., Ferreira, L. and Bunker, J. (2006). *Investigation to Enhance Sustainable Improvements in High Speed Rail Transportation*. [online] http://eprints.qut.edu.au. Available at: http://eprints.qut.edu.au/6007/1/6007_1.pdf [Accessed 1 Dec. 2019].

Cavaignac, L. and Petiot, R. (2017). A quarter century of Data Envelopment Analysis applied to the transport sector: A bibliometric analysis. *Socio-Economic Planning Sciences*, [online] 57, pp.84-96. Available at: https://www.sciencedirect.com/science/article/pii/S0038012116302816 [Accessed 4 Aug. 2019].

Cbsnews.com. (2019). *100 Dead In German Train Wreck*. [online] Available at: https://www.cbsnews.com/news/100-dead-in-german-train-wreck/ [Accessed 8 Aug. 2019].

Cer.be (2018), *Employability in the face of demographic change – prospects for the European rail sector a practical guide to design the future* (2011) Available at: http://www.cer.be/sites/default/files/publication/2114_1295603375_Employability-guide-EN_1_.pdf [Accessed 23 October 2018].

Cer.be. (2019). [online] Available at: http://www.cer.be/sites/default/files/publication/Facts%20and%20figures%202014.pdf [Accessed 13 Aug. 2019].

Cer.be. (2019b). [online] Available at: http://www.cer.be/sites/default/files/publication/2114_1295603375_Employability-guide-EN_1_.pdf [Accessed 14 Aug. 2019].

Cesaroni, G. (2018). Industry cost efficiency in data envelopment analysis. *Socio-Economic Planning Sciences*, [online] 61, pp.37-43. Available at: https://www.sciencedirect.com/science/article/pii/S0038012116300416 [Accessed 6 Aug. 2019].

Cf.cdn.unwto.org. (2019). [online] Available at: http://cf.cdn.unwto.org/sites/all/files/pdf/annual_report_2016_web_0.pdf [Accessed 15 Aug. 2019].

Chang, Y., Park, H., Jeong, J. and Lee, J. (2014). Evaluating economic and environmental efficiency of global airlines: A SBM-DEA approach. *Transportation Research Part D: Transport and Environment*, [online] 27, pp.46-50. Available at: https://www.sciencedirect.com/science/article/pii/S1361920913001636 [Accessed 6 Aug. 2019].

Chang, Y., Lei, S., Teng, J., Zhang, J., Zhang, L. and Xu, X. (2019). The energy use and environmental emissions of high-speed rail transportation in China: A bottom-up modeling. *Energy*, [online] 182, pp.1193-1201. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360544219312526 [Accessed 2 Dec. 2019].

Chang, Y., Yang, Y. and Dong, S. (2018). Comprehensive Sustainability Evaluation of High-Speed Railway (HSR) Construction Projects Based on Unascertained Measure and Analytic Hierarchy Process. *Sustainability*, [online] 10(2), p.408. Available at: https://www.researchgate.net/publication/323245522_sustainability_evaluation_of_high-speed_railway_HSR_construction_projects_based_on_unascertained_measure_and_analytic_hierarchy_process [Accessed 1 Dec. 2019].

Chang, Y., Zhang, N., Danao, D. and Zhang, N. (2013). Environmental efficiency analysis of transportation system in China: A non-radial DEA approach. *Energy Policy*, [online] 58, pp.277-283. Available at: https://www.sciencedirect.com/science/article/pii/S0301421513001651 [Accessed 6 Aug. 2019].

Charnes, A., Cooper, W. and Rhodes, E. (1978). Measuring the efficiency of decision-making units. *European Journal of Operational Research*, [online] 2(6), pp.429-444. Available at: https://www.sciencedirect.com/science/article/abs/pii/0377221778901388 [Accessed 4 Aug. 2019].

Chen, X. (2014). A Sustainability Analysis on the Wuhan-Guangzhou High-Speed Railway in China. *International Journal of Sustainable Transportation*, [online] 9(5), pp.348-363. Available at: https://www.tandfonline.com/doi/abs/10.1080/15568318.2013.797526 [Accessed 1 Dec. 2019].

Chen, Z., Xue, J., Rose, A. and Haynes, K. (2015). The Impact of High-Speed Rail Investment on Economic and Environmental Change in China: A Dynamic CGE Analysis. *SSRN Electronic Journal*. [online] Available at: https://www.sciencedirect.com/science/article/pii/S0965856416306681 [Accessed 6 Aug. 2019].

Cheung, F. (2019). *One Belt, One Road: A brilliant plan*. [online] Clsa.com. Available at: https://www.clsa.com/special/onebeltoneroad/ [Accessed 9 Aug. 2019].

China.org.cn., (2017), *Five bln trips made on China's bullet trains*, Available at: http://www.china.org.cn/business/2016-07/22/content_38938394.htm [Accessed 12 January 2017].

Chiou, Y., Lan, L. and Yen, B. (2010). A joint measurement of efficiency and effectiveness for non-storable commodities: Integrated data envelopment analysis approaches. *European Journal of Operational Research*, [online] 201(2), pp.477-489. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221709001490 [Accessed 4 Aug. 2019].

Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsier, J., Rothengatter, W. and Sieber, N. (2012). *Reducing Railway Noise Pollution*. [online] Europarl.europa.eu. Available at: http://www.europarl.europa.eu/RegData/etudes/etudes/join/2012/474533/IPOL-TRAN_ET(2012)474533_EN.pdf [Accessed 30 April 2018].

Coelli, T. and Perelman, S. (1999). A comparison of parametric and non-parametric distance functions: With application to European railways. *European Journal of Operational Research*, [online] 117(2), pp.326-339. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221798002719 [Accessed 4 Aug. 2019].

COMM (2010) *Europe 2020 – EU-wide headline targets for economic growth - European commission*. Available at: http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm [Accessed 23 October 2016].

Compare Hare. (2019). Annual Global Road Crash Statistics. [online] Available at: https://www.comparehare.co.uk/annual-global-road-crash-statistics/ [Accessed 7 Sep. 2019].

Comparison of cross section of Japanese N700-I and European high-speed train. (2019). [image] Available at: http://www.jterc.or.jp/english/kokusai/conferences/pdf/120113_morimura_pres.pdf [Accessed 8 Aug. 2019].

Cook, W., Tone, K. and Zhu, J. (2014). Data envelopment analysis: Prior to choosing a model. *Omega*, [online] 44, pp.1-4. Available at: https://www.sciencedirect.com/science/article/pii/S0305048313000947 [Accessed 4 Aug. 2019].

Cooper, W., Seiford, L. and Tone, K. (2006). *Introduction to Data Envelopment Analysis and Its Uses*. Boston, MA: Springer Science+Business Media, Inc.

Core.ac.uk. (2019). [online] Available at: https://core.ac.uk/download/pdf/83926257.pdf [Accessed 4 Aug. 2019].

countryeconomy.com. (2019). *Taiwan - Population 2017*. [online] Available at: https://countryeconomy.com/demography/population/taiwan [Accessed 21 Aug. 2019].

Cox, P. (2013). *Moving People*. London: Zed Books, pp.10, 56.

Cui, Q. and Li, Y. (2014). The evaluation of transportation energy efficiency: An application of three-stage virtual frontier DEA. *Transportation Research Part D: Transport and Environment*, [online] 29, pp.1-11. Available at: https://www.sciencedirect.com/science/article/pii/S1361920914000236 [Accessed 6 Aug. 2019].

Danger-ahead.railfan.net. (2019). *Eschede Special Feature*. [online] Available at: http://danger-ahead.railfan.net/features/eschede.htm [Accessed 13 Aug. 2019].

Data.worldbank.org. (2019). *GDP per capita (constant 2010 US$)* | *Data*. [online] Available at:

https://data.worldbank.org/indicator/NY.GDP.PCAP.KD?locations=SA [Accessed 21 Aug. 2019].

Data.worldbank.org. (2019b). *Population density (people per sq. km of land area) | Data*. [online] Available at: https://data.worldbank.org/indicator/EN.POP.DNST?locations=AF-DE-IT-CN-FR-KR-ES-NL-JP-TR-US&name_desc=false [Accessed 21 Aug. 2019].

Debrezion, G., Rietveld, P. and Eric A. J. H. Pels (2016) 'The impact of railway stations on residential and commercial property value: A Meta Analysis', *SSRN Electronic Journal*, doi: 10.2139/ssrn.516742. http://papers.tinbergen.nl/04023.pdf [Accessed 24 November 2016].

De Consommateurs, 60 M. (2017) *La saison des retards de TGV est arrivée | 60 Millions de Consommateurs*. Available at: http://www.60millions-mag.com/2016/07/04/la-saison-des-retards-de-tgv-est-arrivee-10549 [Accessed 12 January 2017].

Denis, E.G. (2013) *The reason for rail*. Available at: http://www.iso.org/iso/home/news_index/news_archive/news.htm?refid=Ref1793 [Accessed 12 January 2017].

Dewberryjes.blogspot.com. (2019). *Railway track technology*. [online] Available at: http://dewberryjes.blogspot.com/2017/04/railway-track-technology.html [Accessed 6 Dec. 2019].

Djordjević, B., Krmac, E. and Mlinarić, T. (2018). Non-radial DEA model: A new approach to evaluation of safety at railway level crossings. *Safety Science*, [online] 103, pp.234-246. Available at: https://www.sciencedirect.com/science/article/pii/S0925753517302266 [Accessed 6 Aug. 2019].

Docplayer.fr. (2019). *High Speed Rail contribution to Sustainable Mobility - PDF*. [online] Available at: https://docplayer.fr/3506286-High-speed-rail-contribution-to-sustainable-mobility.html [Accessed 11 Aug. 2019].

Documents.worldbank.org. (2019). [online] Available at: http://documents.worldbank.org/curated/en/451551468241176543/pdf/932270BRI0Box30ffic020140final000EN.pdf [Accessed 9 Aug. 2019].

Doomernik, J. (2015). Performance and Efficiency of High-speed Rail Systems. *Transportation Research Procedia*, [online] 8, pp.136-144. Available at: https://www.sciencedirect.com/science/article/pii/S2352146515001258 [Accessed 6 Aug. 2019].

Dspace.lboro.ac.uk. (2019). [online] Available at: https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/6006/1/tilt_soa_roger.pdf [Accessed 9 Aug. 2019].

Dumas.ccsd.cnrs.fr. (2019). [online] Available at: https://dumas.ccsd.cnrs.fr/dumas-00793156/document [Accessed 4 Aug. 2019].

Dutzik, T. (2010) *Next stop: California the benefits of high-speed rail around the world and what's in store for California*. Available at: http://www.calpirgstudents.org/sites/student/files/reports/Next-Stop-California.pdf [Accessed 24 November 2016].

Džambas, T., Lakušić, S. and Dragčević, V. (2018). Traffic noise analysis in railway station zones. *Applied Acoustics*, [online] 137, pp.27-32. Available at: https://www.sciencedirect.com/science/article/pii/S0003682X17310964 [Accessed 1 May 2018].

Ec.europa.eu. (2019a). [online] Available at: http://ec.europa.eu/transport/sites/transport/files/themes/infrastructure/studies/doc/2010_high_speed_rail_en.pdf [Accessed 3 August 2019].

Ec.europa.eu. (2019b). *Resource Efficiency - Environment - European Commission*. [online] Available at: http://ec.europa.eu/environment/resource_efficiency/ [Accessed 3 August 2019].

Ec.europa.eu. (2019c). [online] Available at: https://ec.europa.eu/transport/sites/transport/files/themes/infrastructure/studies/doc/2010_high_speed_rail_en.pdf [Accessed 8 Aug. 2019].

Ec.europa.eu. (2019e). *Trans-European Transport Network TENTEC - Transport Facts & Figures - European Commission*. [online] Available at: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/site/en/facts_and_figures.html [Accessed 13 Aug. 2019].

edoc.pub. (2019). *The Railway Track - PDF Free Download*. [online] Available at: https://edoc.pub/the-railway-track-3-pdf-free.html [Accessed 4 Aug. 2019].

Electric-rly-society.org.uk. (2019). *The History of the French High Speed Rail Network and TGV* | *Electric Railway Society*. [online] Available at: https://electric-rly-society.org.uk/the-history-of-the-french-high-speed-rail-network-and-tgv/ [Accessed 8 Aug. 2019].

Emrouznejad, A. and Thanassoulis, E. (2011). *PIM-DEAsoft-V3.0 User Guide*. PIm-Limited.

Emrouznejad, A. and Yang, G. (2018). A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. *Socio-Economic Planning Sciences*, [online] 61, pp.4-8. Available at: https://www.sciencedirect.com/science/article/pii/S0038012117300174 [Accessed 4 Aug. 2019].

Ems.expertgrupp.se. (2019). [online] Available at: http://www.ems.expertgrupp.se/Uploads/Documents/6-mars/EMS-2012_1%20till-webben.pdf [Accessed 7 Aug. 2019].

English.chosun.com. (2019). *KTX Clocks Up Over 414 Million Passengers in a Decade*. [online] Available at: http://english.chosun.com/site/data/html_dir/2014/03/31/2014033101291.html [Accessed 24 Oct. 2019].

Eurail. (2019). *TGV high-speed train*. [online] Available at: http://www.eurail.com/europe-by-train/high-speed-trains/tgv [Accessed 7 Aug. 2019].

Eurail. (2019b). *How to Get From Rome to Florence by Train*. [online] Available at: https://www.eurail.com/en/get-inspired/popular-routes/how-get-rome-florence-train#train-options [Accessed 9 Aug. 2019].

Eurail. (2019c). *Germany By Train*. [online] Available at: https://www.eurail.com/en/get-inspired/top-destinations/germany-train [Accessed 8 Aug. 2019].

Europarl.europa.eu. (2019). [online] Available at: http://www.europarl.europa.eu/RegData/etudes/etudes/join/2012/474533/IPOL-TRAN_ET(2012)474533_EN.pdf [Accessed 8 Aug. 2019].

Europe, h. (2019). *Deutsche Bahn takes over Berlin Linien Bus*. [online] Europebyrail.eu. Available at: https://www.europebyrail.eu/deutsche-bahn-takes-over-berlin-linien-bus/ [Accessed 8 Aug. 2019].

EUROPEAN AUTOMOBILE ASSOCIATION, (2016) "Passenger Car Fleet Per Capita" ACEA. Available from http://www.acea.be/statistics/tag/category/passenger-car-fleet-per-capita [Accessed 6 May 2016].

European Commission (2010) "High Speed Rail Europe" A Sustainable Link between Citizens. Available from http://ec.europa.eu/transport/themes/infrastructure/studies/doc/2010_high_speed_rail_en.pdf [Accessed 6 May 2016].

European Commission (2001), *European transport policy for 2010: Time to decide* (2001) Available at: http://ec.europa.eu/transport/sites/transport/files/themes/strategies/doc/2001_white_paper/lb_com_2001_0370_en.pdf [Accessed 12 January 2017].

European Commission, (2012), *Implementation of the Regulation on Rail Passenger's Rights,* Available at: http://www.cit-rail.org/files/public/.../FINAL_CER_Brochure_PassengersRR_v07.pdf? cid [Accessed 12 January 2017].

European Commission, (2013b), *The Performing Rail infrastructure manager*, Available at: http://ec.europa.eu/transport/sites/transport/files/media/publications/doc/2013-the-performing-rail-infrastructure-manager-lo-res.pdf [Accessed 12 January 2017].

European Conference of Ministers of Transport, (1998) "Efficient Transport for Europe". Paris: OECD Publications pp. 11, 23-34, 45-71.

European Environment Agency. (2016). *Land take*. [online] Available at: http://www.eea.europa.eu/publications/ENVISSUENo12/page011.html [Accessed 12 July 2017].

Eurorailways.com. (2019). *Paris to Marseille Train Tickets by Euro Railways*. [online] Available at: http://www.eurorailways.com/train-tickets/D-FR-FR-MRS-PAR-R-paris-to-marseille.html [Accessed 8 Aug. 2019].

Eurostar, (2016) *Eurostar Service Quality Performance Report 2015-2016* (2016) Available at: http://www.eurostar.com/sites/default/files/eurostar_service_quality_report.pdf [Accessed 12 January 2017].

Eurostat, (2016), *Passenger transport statistics,* Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Number_of_persons_killed_and_injured_by_type_of_accident_and_category_of_persons_in_EU-28,_2014_final.png [Accessed 12 January 2017].

Events.uic.org. (2019). [online] Available at: https://events.uic.org/IMG/pdf/07_renfe_reversible_substations_conventional_lines_ed2_delafuente.pdf [Accessed 8 Aug. 2019].

Fan, Y., Li, Z., Pei, J., Li, H. and Sun, J. (2015). Applying systems thinking approach to accident analysis in China: Case study of “7.23” Yong-Tai-Wen High-Speed train accident. *Safety Science*, [online] 76, pp.190-201. Available at: https://www.sciencedirect.com/science/article/pii/S0925753515000454 [Accessed 9 Aug. 2019].

Focustaiwan.tw. (2019a). *Last Taipei-Kaohsiung air service to be discontinued | Latest | FOCUS TAIWAN - CNA ENGLISH NEWS*. [online] Available at: http://focustaiwan.tw/news/aall/201206250041.aspx [Accessed 23 Oct. 2019].

Focustaiwan.tw. (2019b). *High speed train runs on wrong track, first time ever | Society | FOCUS TAIWAN - CNA ENGLISH NEWS*. [online] Available at: http://focustaiwan.tw/news/asoc/201705130019.aspx [Accessed 23 Oct. 2019].

Førsund, F. (2018). Economic interpretations of DEA. *Socio-Economic Planning Sciences*, [online] 61, pp.9-15. Available at: https://www.sciencedirect.com/science/article/pii/S0038012116300283 [Accessed 4 Aug. 2019].

Ft.com. (2018), *Urban development: Emphasis on regeneration attracts interest from abroad | Financial Times*. [online] Available at: http://www.ft.com/cms/s/0/61843d9a-80d8-11e2-9fae-00144feabdc0.html?siteedition=uk#axzz4HnuZpSwa [Accessed 3 August 2019].

Fu, H., Qu, Y. and Pan, Y. (2018). Efficiency of Cassava Production in China: Empirical Analysis of Field Surveys from Six Provinces. *Applied Sciences*, [online] 8(8), p.1356. Available at: https://www.mdpi.com/2076-3417/8/8/1356/htm? [Accessed 11 Dec. 2019].

Eringa, P., (2016), *ProRail… on the right track,* European Railway Review, Russel publishing Ltd, England, Issue 3, p.19.

Garcia, A. (2010). *High speed, energy consumption and emissions*. [online] Shop-etf.com. Available at: http://www.shop-etf.com/en/high-speed-energy-consumption-and-emissions.html [Accessed 12 July 2017].

Garlier de Fallectans, T. (2016). *Workshops - UIC Sustainable Development Conference 2016*. [online] Uic-environment.org. Available at: http://www.uic-environment.org/workshops#Recyclability-of-Rolling-stock [Accessed 12 July 2017].

Giesler, N. (2011). *HS2 London to the West Midlands Appraisal of Sustainability*. [online] Gov.uk. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/370568/HS2_London_to_the_West_Midlands-_sustainability_appraisal.pdf [Accessed 30 April 2018].

Global Rail News. (2019). *Consortia picked for Lyon-Turin rail link tunnelling work | Global Rail News*. [online] Available at: https://www.globalrailnews.com/2018/02/08/consortium-picked-for-lyon-turin-rail-link-tunnelling-work/ [Accessed 9 Aug. 2019].

Global Railway Review. (2019). *The need for speed*. [online] Available at: https://www.globalrailwayreview.com/article/2509/the-need-for-speed/" [Accessed 9 Aug. 2019].

Goeuro.co.uk. (2019). *Global High-Speed Train Ranking*. [online] Available at: https://www.goeuro.co.uk/trains/high-speed#connections [Accessed 7 Aug. 2019].

GOV.UK. (2018) *HS2: A 'catalyst for economic prosperity'*. Available at: https://www.gov.uk/government/news/hs2-a-catalyst-for-economic-prosperity [Accessed 23 October 2018].

Gov.uk. (2019b). [online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/421337/vls-2014.pdf [Accessed 3 August 2019].

Gov.uk. (2019c). [online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228953/7226.pdf [Accessed 14 Aug. 2019].

GOV.UK. (2019a). *Road length statistics (RDL)*. [online] Available at: https://www.gov.uk/government/statistical-data-sets/rdl02-road-lengths-kms#table-rdl0201 [Accessed 3 August 2019].

GOV.UK. (2019b). *HS2 Phase Two: from the West Midlands to Leeds and Manchester*. [online] Available at: https://www.gov.uk/government/collections/hs2-phase-two-from-the-west-midlands-to-leeds-and-manchester [Accessed 10 Aug. 2019].

GOV.UK. (2019c). *HS2: a 'catalyst for economic prosperity'*. [online] Available at: https://www.gov.uk/government/news/hs2-a-catalyst-for-economic-prosperity [Accessed 14 Aug. 2019].

Graham, D. (2008). Productivity and efficiency in urban railways: Parametric and non-parametric estimates. *Transportation Research Part E: Logistics and Transportation Review*, [online] 44(1), pp.84-99. Available at: https://www.sciencedirect.com/science/article/pii/S1366554506000366 [Accessed 6 Aug. 2019].

Growitsch, C. and Wetzel, H. (2009). Testing for Economies of Scope in European Railways an Efficiency Analysis. *Journal of Transport Economics and Policy*, 43(Part1), pp.1-24.

Guirao, B. and Campa, J. (2014). The construction of a HSR network using a ranking methodology to prioritise corridors. *Land Use Policy*, [online] 38, pp.290-299. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0264837713002536 [Accessed 2 Dec. 2019].

Guo, X., Lu, C., Lee, J. and Chiu, Y. (2017). Applying the dynamic DEA model to evaluate the energy efficiency of OECD countries and China. *Energy*, [online] 134, pp.392-399. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360544217310344 [Accessed 6 Aug. 2019].

Ha, H., Yoshida, Y. and Zhang, A. (2011). Social efficiency benchmarking of Japanese domestic transport services: A comparison of rail and air. *Transportation Research Part D: Transport and Environment*, [online] 16(7), pp.554-561. Available at: https://www.worldtransitresearch.info/research/3959/ [Accessed 6 Aug. 2019].

Hernández-Sancho, F., Molinos-Senante, M. and Sala-Garrido, R. (2011). Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach. *Science of The Total Environment*, [online] 409(14), pp.2693-2699. Available at: https://www.sciencedirect.com/science/article/pii/S0048969711003755 [Accessed 6 Aug. 2019].

History.amtrak.com. (2019). *Happy 15th Anniversary, Acela Express! — Amtrak: History of America's Railroad*. [online] Available at: https://history.amtrak.com/blogs/blog/happy-15th-anniversary-acela-express [Accessed 9 Aug. 2019].

Hoyle, B. and Knowles, R. (1998). *Modern transport geography*. Chichester: John Wiley & Sons, p.105, pp.333-339.

https://www.justtrains.net. (2019). *Just Trains - CRH380D High Speed Train*. [online] Available at: https://www.justtrains.net/product/crh-380d-high-speed-train [Accessed 7 Aug. 2019].

Huang, N. (2015) *Most visited countries in the world 2015 - A top 10*. Available at: http://www.wildjunket.com/most-visited-countries-2015/ [Accessed 22 December 2016].

Iglesias, E., Thompson, D. and Smith, M. (2017). Component-based model to predict aerodynamic noise from high-speed train pantographs. *Journal of Sound and Vibration*, [online] 394, pp.280-305. Available at: https://www.sciencedirect.com/science/article/pii/S0022460X17300512 [Accessed 1 May 2015].

International Business Times UK. (2019). *Top 10 Spectacular High Speed Trains from around the World [PHOTOS]*. [online] Available at: http://www.ibtimes.co.uk/10-spectacular-high-speed-trains-around-world-331421 [Accessed 7 Aug. 2019].

International Railway Journal. (2019). *JR Central previews N700S Shinkansen train - International Railway Journal*. [online] Available at: https://www.railjournal.com/passenger/high-speed/jr-central-previews-n700s-shinkansen-train/ [Accessed 7 Aug. 2019].

International Railway Journal. (2019b). *France faces tough choices over future of TGV - International Railway Journal*. [online] Available at: https://www.railjournal.com/in_depth/france-faces-tough-choices-over-future-of-tgv/ [Accessed 8 Aug. 2019].

International Railway Journal. (2019c). *SNCF welcomes 2 billionth TGV passenger - International Railway Journal*. [online] Available at: http://www.railjournal.com/index.php/high-speed/sncf-welcomes-its-2-billionth-tgv-passenger.html" [Accessed 8 Aug. 2019].

International Railway Journal. (2019d). *Spain pushes ahead with high-speed plans - International Railway Journal*. [online] Available at: http://www.railjournal.com/index.php/high-speed/spain-pushes-ahead-with-high-speed-plans.html [Accessed 8 Aug. 2019].

International Railway Journal. (2019e). *350km/h operation resumes on Beijing - Shanghai high-speed line - International Railway Journal*. [online] Available at: http://www.railjournal.com/index.php/asia/350km-h-operation-resumes-on-beijing-shanghai-high-speed-line.html [Accessed 9 Aug. 2019].

International Railway Journal. (2019f). *Expansion and reform reshape Turkey's railways - International Railway Journal*. [online] Available at: http://www.railjournal.com/index.php/high-speed/expansion-and-reform-reshape-turkeys-railways.html" [Accessed 9 Aug. 2019].

Ipfs.io. (2019). *Tōkaidō Shinkansen*. [online] Available at: https://ipfs.io/ipfs/QmXoypizjW3WknFiJnKLwHCnL72vedxjQkDDP1mXWo6uco/wiki/Tokaido_Shinkansen.html [Accessed 7 Aug. 2019].

Ipcc.ch. (2019). [online] Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf [Accessed 4 Aug. 2019].

Ertms.net. (2019). *ERTMS | The European Railway Traffic Management System*. [online] Available at: http://www.ertms.net/wpcontent/uploads/2014/09/ERTMS_Factsheet_4_ERTMS_deployment_Italy.pdf [Accessed 9 Aug. 2019].

ISO. (2019). *The reason for rail*. [online] Available at: https://www.iso.org/news/2013/11/Ref1793.html [Accessed 8 Aug. 2019].

ITV NEWS, (9TH February 2016) "German Train Crash: The latest in a history of rail accidents". Available from http://www.itv.com/news/2016-02-09/a-history-of-german-train-disasters/ [Accessed 6 May 2016].

Japanese Railway Technology Today. (2001). Tokyo: Railway Technical Research Institute, pp. 14,18, 20, 21, 31, 32, 90, 119,126

Japanvisitor.com. (2019). *Nozomi Shinkansen Train | JapanVisitor Japan Travel Guide*. [online] Available at: https://www.japanvisitor.com/japan-transport/nozomi-shinkansen [Accessed 7 Aug. 2019].

Jehanno, A., Palmer, D., and James, C. (2011)" High Speed Rail and Sustainability". UIC: Paris, UIC, CER. Available from www.old.uic.org/download.php/publication/531E.pdf [Accessed 30 April 2016].

Jehanno, A. (2011). *High Speed Rail and Sustainable Mobility*. [ebook] Paris: UIC. Available at: http://www.apta.com/mc/hsr/previous/2011/presentations/Presentations/High-Speed-Rail-and-Sustainable-Mobility-A-Focus-on-Environmental-and-Social-Issues.pdf [Accessed 30 April 2018].

Jiang, B. and Li, J. (2009). DEA-based Performance Measurement of Seaports in Northeast Asia: Radial and Non-radial Approach. *The Asian Journal of Shipping and Logistics*, [online] 25(2), pp.219-236. Available at: https://www.sciencedirect.com/science/article/pii/S2092521209800035 [Accessed 7 Aug. 2019].

Jitsuzumi, T. and Nakamura, A. (2010). Causes of inefficiency in Japanese railways: Application of DEA for managers and policymakers. *Socio-Economic Planning Sciences*, [online] 44(3), pp.161-173. Available at: https://www.sciencedirect.com/science/article/pii/S0038012109000457 [Accessed 6 Aug. 2019].

Jong, J.., Lin, T.., Lee, C. and Hu, H. (2010) 'The analysis of train reliability for the Taiwan high speed rail', *Computers in Railways XII*, doi: 10.2495/cr100171. Available at: www.witpress.com/elibrary/wit-transactions-on-the-built-environment/114/21419 [Accessed 12 January 2017].

Juo, J., Lin, Y. and Chen, T. (2013). Productivity change of Taiwanese farmers' credit unions: a nonparametric metafrontier Malmquist–Luenberger productivity indicator. *Central European Journal of Operations Research*, [online] 23(1), pp.125-147. Available at: https://link.springer.com/article/10.1007%2Fs10100-013-0307-6 [Accessed 11 Dec. 2019].

Kamga, C. and Yazici, M. (2014). Achieving environmental sustainability beyond technological improvements: Potential role of high-speed rail in the United States of America. *Transportation Research Part D: Transport and Environment*, [online] 31, pp.148-164. Available at: https://www.sciencedirect.com/science/article/pii/S1361920914000765 [Accessed 2 Dec. 2019].

Kampman, B., Rijkee, X., Pridmore, A., Hulskotte, J. (2009) “EU Transport GHG Routes to 2050”pdf. Available from http://www.eutransportghg2050.eu/cms/assets/EU-Transport-GHG-2050-Paper-4-Operational-options-30-10-09.pdf [Accessed 6 May 2016].

Karlaftis, M. (2004). A DEA approach for evaluating the efficiency and effectiveness of urban transit systems. *European Journal of Operational Research*, [online] 152(2), pp.354-364. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221703000298 [Accessed 6 Aug. 2019].

Kastaniotis, G., Maragos, E., Douligeris, C. and Despotis, D. (2012). Using data envelopment analysis to evaluate the efficiency of web caching object replacement strategies. *Journal of Network and Computer Applications*, [online] 35(2), pp.803-817. Available at: https://www.sciencedirect.com/science/article/pii/S1084804511002281?via%3Dihub [Accessed 11 Dec. 2019].

Katz-Rosene, R. (2016). To build or not to build? Competing narratives of high-speed rail development in Canada. *Mobilities*, [online] 12(5), pp.758-777. Available at: https://www.tandfonline.com/doi/abs/10.1080/17450101.2016.1175757 [Accessed 1 Dec. 2019].

Kiriazidis, T.1994, *European transport: problems and policies,* Publisher: Ashgate, p.7.

Korail, 2010, *Sustainability Report,* Available at: http://info.korail.com/upload/contents/www/data/www_040701000000/2010_result(eng).pdf [Accessed 12 January 2017].

Korea JoongAng Daily. (2019a). *Bullet trains coming to a town near you by 2020*. [online] Available at: http://koreajoongangdaily.joins.com/news/article/article.aspx?aid=2925474 [Accessed 23 Oct. 2019].

Korea JoongAng Daily. (2019b). *Bullet trains steal planes’ thunder*. [online] Available at:

http://koreajoongangdaily.joins.com/news/article/article.aspx?aid=2903012 [Accessed 24 Oct. 2019].

koreatimes. (2019). *Jeju Hesistant on Underground KTX Project*. [online] Available at: http://www.koreatimes.co.kr/www/news/nation/2010/03/117_58506.html [Accessed 24 Oct. 2019].

Lai, P., Potter, A., Beynon, M. and Beresford, A. (2015). Evaluating the efficiency performance of airports using an integrated AHP/DEA-AR technique. *Transport Policy*, [online] 42, pp.75-85. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0967070X15300081 [Accessed 6 Aug. 2019].

Lan, L. and Lin, E. (2006). *Journal of Transport Economics and Policy*, 40(Part 3), pp.383-408.

Lan, L. and Lin, E. (2005). MEASURING RAILWAY PERFORMANCE WITH ADJUSTMENT OF ENVIRONMENTAL EFFECTS, DATA NOISE AND SLACKS. *Transportmetrica*, [online] 1(2), pp.161-189. Available at: https://www.researchgate.net/publication/46557356_Performance_Measurement_for_Railway_Transport_Stochastic_Distance_Functions_with_Inefficiency_and_Ineffectiveness_Effects [Accessed 4 Aug. 2019].

Lee, T., Yeo, G. and Thai, V. (2014). Environmental efficiency analysis of port cities: Slacks-based measure data envelopment analysis approach. *Transport Policy*, [online] 33, pp.82-88. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0967070X14000407 [Accessed 6 Aug. 2019].

Liu, W., Zhou, Z., Ma, C., Liu, D. and Shen, W. (2015). Two-stage DEA models with undesirable input-intermediate-outputs. *Omega*, [online] 56, pp.74-87. Available at: https://www.sciencedirect.com/science/article/pii/S0305048315000547 [Accessed 6 Aug. 2019].

Liu, X., Schraven, D., de Bruijne, M., de Jong, M. and Hertogh, M. (2019). Navigating Transitions for Sustainable Infrastructures—The Case of a New High-Speed Railway Station in Jingmen, China. *Sustainability*, [online] 11(15), p.4197. Available at: https://www.mdpi.com/2071-1050/11/15/4197 [Accessed 1 Dec. 2019].

Loizides, J. and Tsionas, E. (2002). Productivity growth in European railways: a new approach. *Transportation Research Part A: Policy and Practice*, [online] 36(7), pp.633-644. Available at: https://www.sciencedirect.com/science/article/pii/S0965856401000271 [Accessed 6 Aug. 2019].

Lou, J., Gui, A., Rollo, J., Moh, A., Lou, L., Lin, R., Zhu, K., Goods, C., Luo, K., Xu, E., Meng, A., Wong, V., Hu, B. and Shi, C. (2011) *China high-speed rail*. Available at: http://www.morganstanley.com/views/perspectives/China_HighSpeed_Rail.pdf [Accessed 23 October 2016].

Ltd, E.I. (2015) *Train deals*. Available at: http://www.eurostar.com/uk-en/about-eurostar/press-office/press-releases/2015/eurostar-reports-continuing-growth-in-2014 [Accessed 12 January 2017].

Ltd, D. (2019). *Integrating ETCS Level 2 with TVM430 on TGV Est*. [online] Railway Gazette. Available at: http://www.railwaygazette.com/news/single-view/view/integrating-etcs-level-2-with-tvm430-on-tgv-est.html [Accessed 7 Aug. 2019].

Ltd, D. (2019b). *Debt burden tempers SNCF growth in 2017*. [online] Railway Gazette. Available at: https://www.railwaygazette.com/news/single-view/view/debt-burden-tempers-sncf-growth-in-2017.html [Accessed 8 Aug. 2019].

Ltd, D. (2019c). *Trenitalia unveils Frecciarossa 1000*. [online] Railway Gazette. Available at: http://www.railwaygazette.com/news/passenger/single-view/view/trenitalia-unveils-frecciarossa-1000.html [Accessed 9 Aug. 2019].

Lucas K., 2000, *Running on Empty, Transport, social exclusion and environmental justice*, Publisher: Policy Press, Bristol, England, p.21.

Lukaszewicz, P. and Andersson, E. (2008). *Energy Efficiency of High-speed Rail Will higher speed cause increased energy consumption?*. [online] Available at: http://uic.org/apps/presentation/lukaszewicz.pdf [Accessed 12 July 2017].

Lynch, T. (1998). *High speed rail in the US*. Amsterdam: Gordon & Breach, p.83.

MADDISON, DAVID and PEARCE, DAVID (1996) "The True Costs of Road Transport". Blueprint 5, London: Earthscan, pp 11-18, 51-61, 84-99, 132-190.

Mahdiloo, M., Toloo, M., Duong, T., Farzipoor Saen, R. and Tatham, P. (2018). Integrated data envelopment analysis: Linear vs. nonlinear model. *European Journal of Operational Research*, [online] 268(1), pp.255-267. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221718300080 [Accessed 6 Aug. 2019].

Mahmoud, D.., Mousa, A., Aswan, A.A., Ägypten, Jürgen, ., Berichter, T., Berichter, S., Hafez, .M. and Aly, F. (2012) *Opportunities for high-speed railways in developing and emerging countries: A case study Egypt*. Available at: https://depositonce.tu-berlin.de/bitstream/11303/3640/1/Dokument_9.pdf [Accessed 13 January 2017].

Malikov, E., Restrepo-Tobon, D. and Kumbhakar, S. (2013). Estimation of Banking Technology Under Credit Uncertainty. *SSRN Electronic Journal*. [online] Available at: https://mpra.ub.uni-muenchen.de/55991/1/MPRA_paper_55991.pdf? [Accessed 11 Dec. 2019].

Marchetti, D. and Wanke, P. (2017). Brazil's rail freight transport: Efficiency analysis using two-stage DEA and cluster-driven public policies. *Socio-Economic Planning Sciences*, [online] 59, pp.26-42. Available at: https://www.sciencedirect.com/science/article/pii/S0038012116300490 [Accessed 6 Aug. 2019].

Martens, A., Wedemann, J., Meunier, N. and Leclere, A. (2018). *HIGH SPEED TRAIN NOISE - SOUND SOURCE LOCALIZATION AT FAST PASSING TRAINS*. [online] Available at: http://webistem.com/acoustics2008/acoustics2008/cd1/data/fa2002-sevilla/forumacusticum/archivos/noi03007.pdf [Accessed 30 April 2018].

Media, D. (2017) *Korail sets out its 2015 vision*. Available at: http://www.railwaygazette.com/news/single-view/view/korail-sets-out-its-2015-vision.html [Accessed 12 January 2017].

Metro.co.uk. (2019). *Train travels right through hole in 19-storey block of flats in China | Metro News*. [online] Available at: https://metro.co.uk/2017/03/20/train-travels-right-through-hole-in-19-storey-block-of-flats-6521315/ [Accessed 7 Dec. 2019].

Micheli, G. and Farné, S. (2016). Urban railway traffic noise: Looking for the minimum cost for the whole community. *Applied Acoustics*, [online] 113, pp.121-131. Available at: https://www.sciencedirect.com/science/article/pii/S0003682X1630175X [Accessed 1 May 2018].

Mohajeri, N. and Amin, G. (2010). Railway station site selection using analytical hierarchy process and data envelopment analysis. *Computers & Industrial Engineering*, [online] 59(1), pp.107-114. Available at: https://www.sciencedirect.com/science/article/abs/pii/S036083521000077X [Accessed 6 Aug. 2019].

Monzón, A., Ortega, E. and López, E. (2010) *SOCIAL IMPACTS OF HIGH SPEED RAIL PROJECTS: ADDRESSING SPATIAL EQUITY EFFECTS*. Available at: http://oa.upm.es/7401/3/INVE_MEM_2010_75870.pdf [Accessed 29 November 2016].

Muldowney, S. (2016) *Bullet trains and the economics of high-speed railways*. Available at: https://intheblack.com/articles/2015/09/01/bullet-trains-and-the-economics-of-high-speed-railways [Accessed 27 November 2016].

Murphy, J., (2016), *Creating a more comfortable working environment for train drivers*, RTM, Cognitive Publishing Ltd, Manchester, p.77.

Nataraja, N. and Johnson, A. (2011). Guidelines for using variable selection techniques in data envelopment analysis. *European Journal of Operational Research*, [online] 215(3), pp.662-669. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221711006011 [Accessed 9 Oct. 2019].

News.bbc.co.uk. (2019). *BBC NEWS | World | Europe | Trains in Spain signal the future*. [online] Available at: http://news.bbc.co.uk/1/hi/world/europe/8268003.stm [Accessed 8 Aug. 2019].

NewsComAu. (2019). *French TGV train derails near Strasbourg: ‘Excessive speed’ blamed*. [online] Available at: https://www.news.com.au/world/europe/ten-die-as-french-highspeed-train-derails/news-story/8554e5b749d5a9d4b76baf4f81282070 [Accessed 8 Aug. 2019].

News, T. (2019). *Taiwan’s Pingtung high-speed rail line ... | Taiwan News*. [online] Taiwan News. Available at: https://www.taiwannews.com.tw/en/news/3785801 [Accessed 22 Oct. 2019].

nippon.com. (2019). *Shinkansen Route Map*. [online] Available at: https://www.nippon.com/en/features/h00077/shinkansen-route-map.html [Accessed 7 Aug. 2019].

Nkt.com. (2019). [online] Available at: https://www.nkt.com/fileadmin/user_upload/01_Page_images_global/general_images_pages/Success_Stories/Reference-Flyer-Bejing-Shanghai.pdf [Accessed 9 Aug. 2019].

Nunen, J., Huijbregts, P. and Rietveld, P. (2011). *Transitions towards sustainable mobility*. Berlin: Springer, pp.82-84, 230

Oertli, J. and Hubner, P. (2010). *Railway Noise in Europe a 2010 report on the state of the art*. Paris: UIC, p.12.

Olive Press News Spain. (2019). *Spain's high speed trains stay on track - Olive Press News Spain*. [online] Available at: https://www.theolivepress.es/spain-news/2014/10/17/bullet-trains-stay-on-track/ [Accessed 11 Aug. 2019].

Ollivier, G., Bullock, R., Jing, Y., Sondhri, J., Zhou, N. and Beijing, W.B. (2015) *Chinese high-speed: An evaluation of traffic*. Available at: http://www.railjournal.com/index.php/high-speed/chinese-high-speed-an-evaluation-of-traffic.html [Accessed 13 January 2017].

Olma, S. (2013) *UIC study - night trains 2.0*. Available at: http://www.nachtzug-retten.de/wp-content/uploads/2016/05/2013-04-30_uic_study_night_trains_2.02.pdf [Accessed 22 December 2016].

Openknowledge.worldbank.org. (2019). [online] Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/25483/892000BRI0Box3000china0transport09.pdf?sequence=1&isAllowed=y [Accessed 13 Aug. 2019].

Oum, T., Pathomsiri, S. and Yoshida, Y. (2013). Limitations of DEA-based approach and alternative methods in the measurement and comparison of social efficiency across firms in different transport modes: An empirical study in Japan. *Transportation Research Part E: Logistics and Transportation Review*, [online] 57, pp.16-26. Available at: https://www.sciencedirect.com/science/article/pii/S1366554513000136 [Accessed 6 Aug. 2019].

Pallant, J. (2013). *SPSS survival manual*. 5th ed. London, UK: McGraw-Hill, pp.7, 78, 133-141.

Park, J. and Park, T. (1999). Implementation of Train Communication Network for Korean High Speed Train (KHST). *IFAC Proceedings Volumes*, [online] 32(2), pp.8231-8236. Available at: https://www.sciencedirect.com/science/article/pii/S1474667017574042 [Accessed 7 Aug. 2019].

Pedro, M.J.G., Silva, J., Abreu, D. and Cesur (2014) *A CONTEXTUAL ANALYSIS OF THE IMPACTS OF HIGH SPEED RAIL ON REGIONAL DEVELOPMENT AND MOBILITY*. Available at: http://www.wctrs-society.com/wp/wp-content/uploads/abstracts/rio/selected/3367.pdf [Accessed 12 January 2017].

Pels, E., Nijkamp, P. and Rietveld, P. (2003). Inefficiencies and scale economies of European airport operations. *Transportation Research Part E: Logistics and Transportation Review*, [online] 39(5), pp.341-361. Available at: https://www.sciencedirect.com/science/article/pii/S1366554503000164 [Accessed 6 Aug. 2019].

Perrels, A., Himanen, V., Lee-Gosselin, M. (2008) *Building blocks for sustainable transport: obstacles, trends, solutions*, Bingley, pp 35-36, 40-41, 50.

Pestana Barros, C. and Peypoch, N. (2010). Productivity changes in Portuguese bus companies. *Transport Policy*, [online] 17(5), pp.295-302. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0967070X10000351 [Accessed 6 Aug. 2019].

Peterson, B.O. (2011) 'High speed rail: Track construction considerations', *2011 Joint Rail Conference*, . doi: 10.1115/jrc2011-56021. Available at: www.morganstanley.com/views/perspectives/China_HighSpeed_Rail.pdf [Accessed 29 December 2016].

Pidd, M. (2005). Perversity in public service performance measurement. *International Journal of Productivity and Performance Management*, 54(5/6), pp.482-493.

Pjevčević, D., Vladisavljević, I., Vukadinović, K. and Teodorović, D. (2011). Application of DEA to the analysis of AGV fleet operations in a port container terminal. *Procedia - Social and Behavioral Sciences*, [online] 20, pp.816-825. Available at: https://www.sciencedirect.com/science/article/pii/S1877042811014704 [Accessed 6 Aug. 2019].

Plm.automation.siemens.com. (2019). [online] Available at: http://www.plm.automation.siemens.com/CaseStudyWeb/dispatch/viewResource.html?resourceId=27246 [Accessed 3 August 2019].

Poisson, F., Gautier, P. and Letourneaux, F. (n.d.). *Notes on Numerical Fluid Mechanics and Multidisciplinary Design Noise and Vibration Mitigation for Rail Transportation Systems*. [online] Available at: https://uic.org/cdrom/2008/11_wcrr2008/pdf/S.1.1.4.4.pdf [Accessed 30 April 2018].

PwC, (2017), *Why high-speed rail*, Available at: https://www.pwc.com/gx/en/capital-projects-infrastructure/pdf/gridlines-fall-2011-high-speed-rail.pdf [Accessed 13 January 2017].

Railways. (1995). Sheffield: Advanced Railway Research Centre, p.23.

Railways Challenges to Science and Technology. (1995). London: The Royal Academy of Engineering, p.2.

Railway Gazette. (2019). *South Korea's growing network*. [online] Available at: https://www.railwaygazette.com/news/single-view/view/10/south-koreas-growing-network.html [Accessed 23 Oct. 2019].

Railway-News. (2019). *The Recyclable Train – By Véronique Andriès, Alstom*. [online] Available at: https://railway-news.com/the-recyclable-train [Accessed 3 August 2019].

Railway PRO Communication Platform. (2019a). *High speed rail lines in Turkey will redesign the concept of accessibility*. [online] Available at: https://www.railwaypro.com/wp/high-speed-rail-lines-turkey-will-redesign-concept-accessibility/ [Accessed 9 Aug. 2019].

Railway PRO Communication Platform. (2019b). *Turkey, enormous transport potential at the heart of Eurasian Platform*. [online] Available at: https://www.railwaypro.com/wp/turkey-enormous-transport-potential-heart-eurasian-platform/ [Accessed 9 Aug. 2019].

Railway-technology com., (2017), *TGV South Korea* (2004) Available at: http://www.railway-technology.com/projects/koreatgv/ [Accessed 12 January 2017].

Railway Technology. (2019). *The world's longest high-speed railway lines*. [online] Available at: https://www.railway-technology.com/features/featurethe-worlds-longest-high-speed-railway-lines-4149752/ [Accessed 7 Aug. 2019].

Railway Technology. (2019b). *Talgo Avril Very High Speed Train - Railway Technology*. [online] Available at: http://www.railway-technology.com/projects/talgo-avril-very-high-speed-train/ [Accessed 7 Aug. 2019].

Railway Technology. (2019c). *California High-Speed Rail Network - Railway Technology*. [online] Available at: http://www.railway-technology.com/projects/california/ [Accessed 7 Aug. 2019].

Railway Technology. (2019d). *TGV France High Speed Railways operated by SNCF - Railway Technology*. [online] Available at: https://www.railway-technology.com/projects/frenchtgv/" [Accessed 8 Aug. 2019].

Railway Technology. (2019e). *TGV France High Speed Railways operated by SNCF - Railway Technology*. [online] Available at: https://www.railway-technology.com/projects/frenchtgv/ [Accessed 8 Aug. 2019].

Railway Technology. (2019f). Frecciarossa 1000 Very High-Speed Train - Railway Technology. [online] Available at: https://www.railway-technology.com/projects/frecciarossa-1000-very-high-speed-train/ [Accessed 6 Sep. 2019].

Reason.org. (2019). [online] Available at: https://reason.org/wp-content/uploads/files/high_speed_rail_lessons.pdf [Accessed 4 Aug. 2019].

Renfe.com. (2019). *ATENDO Service*. [online] Available at: http://www.renfe.com/EN/viajeros/atendo/index.html [Accessed 8 Aug. 2019].

Renfe.com. (2019b). [online] Available at: http://www.renfe.com/docs/Informe_anual_2013.pdf [Accessed 21 Aug. 2019].

Renner, M. and Gardner, G. (2010) *Global competitiveness in the rail and transit industry*. Available at: http://www.worldwatch.org/system/files/GlobalCompetitiveness-Rail.pdf [Accessed 23 October 2016].

Revolv, L. (2017). *"Minimum railway curve radius" on Revolvy.com*. [online] Revolvy.com. Available at: https://www.revolvy.com/main/index.php?s=Minimum%20railway%20curve%20radius&item_type=topic [Accessed 12 July 2017].

Rssb.co.uk. (2019). *Rail Sustainable Development Principles*. [online] Available at: https://www.rssb.co.uk/Research-and-Technology/Sustainability/The-Rail-Sustainable-Development-Principles [Accessed 23 Nov. 2019].

Sameni, M., Preston, J. and Khadem Sameni, M. (2016). Evaluating efficiency of passenger railway stations: A DEA approach. *Research in Transportation Business & Management*, [online] 20, pp.33-38. Available at:

https://www.sciencedirect.com/science/article/pii/S2210539516300621 [Accessed 4 Aug. 2019].

Sciencedirect.com. (2019). *Electricity Generation - an overview | ScienceDirect Topics*. [online] Available at: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/electricity-generation [Accessed 9 Aug. 2019].

Scott, N. (2009). *Railway transportation*. New York: Nova Science Publishers, p. 242.

Schar.gmu.edu. (2019). *Kenneth J. Button - CV | Schar School of Policy and Government*. [online] Available at: https://schar.gmu.edu/about/faculty-directory/kenneth-j-button/kenneth-j-button-cv [Accessed 3 August 2019].

Scribd. (2019). *2016 | Train | Rolling Stock*. [online] Available at: https://www.scribd.com/document/390693811/2016 [Accessed 7 Aug. 2019].

Sdt.unwto.org. (2019). *Definition | Sustainable Development of Tourism*. [online] Available at: http://sdt.unwto.org/content/about-us-5 [Accessed 3 August 2019].

Sdt.unwto.org. (2019b). [online] Available at: https://sdt.unwto.org/sites/all/files/docpdf/climate2008.pdf [Accessed 15 Aug. 2019].

Shael (2019). *Talgo 250*. [online] Slideshare.net. Available at: https://www.slideshare.net/ErShael/talgo-250 [Accessed 8 Aug. 2019].

Sheng, X., Zhong, T. and Li, Y. (2017). Vibration and sound radiation of slab high-speed railway tracks subject to a moving harmonic load. *Journal of Sound and Vibration*, [online] 395, pp.160-186. Available at: https://www.sciencedirect.com/science/article/pii/S0022460X17301189 [Accessed 1 May 2018].

Shima, T. (2019). *High-Speed Railways in Asia*. [online] Web.archive.org. Available at: https://web.archive.org/web/20110613163935/http://www.jrtr.net/jrtr48/pdf/f40_Shi.pdf [Accessed 22 Oct. 2019].

Shinkansen, J.J. (no date) *High-speed rail passenger traffic density statistics*. Available at:

http://www.publictransit.us/ptlibrary/trafficdensityHSR/HSRtrafficdensity2010.pdf (Accessed: 23 October 2016).

Shultz, J. (2017). The 2013 Santiago de Compostela Train Crash: High-Speed Derailment, Medical Trauma, and Psychological Aftermath. *Prehospital and Disaster Medicine*, [online] 32(S1), p.S114. Available at: https://www.researchgate.net/publication/289686478_Disaster_complexity_and_the_Santiago_de_Compostela_train_derailment [Accessed 8 Aug. 2019].

Siemens.com. (2019). *Velaro Turkey High-Speed Train | Press | Company | Siemens*. [online] Available at: https://www.siemens.com/press/en/feature/2015/mobility/2015-08-velaro-turkey.php [Accessed 9 Aug. 2019].

Skift.com. (2019). [online] Available at: https://skift.com/wp-content/uploads/2015/06/wttc-june-2015-report.pdf [Accessed 3 August 2019].

Smith, A., Wheat, P. and Smith, G. (2010). The role of international benchmarking in developing rail infrastructure efficiency estimates. *Utilities Policy*, [online] 18(2), pp.86-93. Available at: https://www.sciencedirect.com/science/article/pii/S0957178709000435 [Accessed 4 Aug. 2019].

Soeta, Y. and Shimokura, R. (2013). Survey of interior noise characteristics in various types of trains. *Applied Acoustics*, 74(10), pp.1160-1166.

Song, M., Zhang, G., Zeng, W., Liu, J. and Fang, K. (2016). Railway transportation and environmental efficiency in China. *Transportation Research Part D: Transport and Environment*, [online] 48, pp.488-498. Available at: https://www.sciencedirect.com/science/article/pii/S1361920915000954 [Accessed 4 Aug. 2019].

Stanke, B. (2009) *High speed rail's effect on population distribution in secondary urban areas an analysis of the french urban areas and implications for the California central valley*. Available at: http://www.ca4hsr.org/wp-content/uploads/2009/10/Brian-Stanke-298-High-Speed-Rails-Effect-on-Population-Distribution.pdf [Accessed 23 October 2016].

Statista. (2019). *U.S. motor gasoline and distillate fuel consumption 2018 | Statista*. [online] Available at: https://www.statista.com/statistics/189410/us-gasoline-and-diesel-consumption-for-highway-vehicles-since-1992/ [Accessed 9 Aug. 2019].

studylib.es. (2019). *Informe Anual 2012*. [online] Available at: http://studylib.es/doc/8236056/informe-anual-2012 [Accessed 21 Aug. 2019].

Su, M., Luan, W., Yuan, L., Zhang, R. and Zhang, Z. (2019). Sustainability Development of High-Speed Rail and Airline—Understanding Passengers' Preferences：A Case Study of the Beijing–Shanghai Corridor. *Sustainability*, [online] 11(5), p.1352. Available at: https://www.mdpi.com/2071-1050/11/5/1352 [Accessed 1 Dec. 2019].

Sueyoshi, T. and Goto, M. (2015). DEA environmental assessment in time horizon: Radial approach for Malmquist index measurement on petroleum companies. *Energy Economics*, [online] 51, pp.329-345. Available at: https://www.sciencedirect.com/science/article/pii/S0140988315002194 [Accessed 6 Aug. 2019].

Sueyoshi, T. and Yuan, Y. (2017). Social sustainability measured by intermediate approach for DEA environmental assessment: Chinese regional planning for economic development and pollution prevention. *Energy Economics*, [online] 66, pp.154-166. Available at: https://www.sciencedirect.com/science/article/pii/S0140988317302025 [Accessed 6 Aug. 2019].

Sueyoshi, T., Yuan, Y., Li, A. and Wang, D. (2017). Methodological comparison among radial, non-radial and intermediate approaches for DEA environmental assessment. *Energy Economics*, [online] 67, pp.439-453. Available at: https://www.sciencedirect.com/science/article/pii/S0140988317302554 [Accessed 6 Aug. 2019].

Sufian, F. and Habibullah, M. (2011). Opening the Black Box on Bank Efficiency in China: Does Economic Freedom Matter?. *Global Economic Review*, [online] 40(3), pp.269-298. Available at: https://www.tandfonline.com/doi/abs/10.1080/1226508X.2011.601633 [Accessed 12 Nov. 2019].

Sun, J., Yuan, Y., Yang, R., Ji, X. and Wu, J. (2017). Performance evaluation of Chinese port enterprises under significant environmental concerns: An extended DEA-based analysis. *Transport Policy*, [online] 60, pp.75-86. Available at: https://www.researchgate.net/publication/320767506_Performance_evaluation_of_Chinese_port_enterprises_under_significant_environmental_concerns_An_extended_DEA-based_analysis [Accessed 6 Aug. 2019].

Systraasia.com. (2019). [online] Available at: http://systraasia.com/upload/project/20090105030355.pdf [Accessed 23 Oct. 2019].

Taipeitimes.com. (2019). *THSRC to increase runs, buy more new cars: Ou Chin-der - Taipei Times*. [online] Available at: http://www.taipeitimes.com/News/taiwan/archives/2008/11/22/2003429230 [Accessed 22 Oct. 2019].

Talgo.com. (2019). *Talgo*. [online] Available at: https://www.talgo.com/en/rolling-stock/very-high-speed/avril/ [Accessed 8 Aug. 2019].

Tan, P., Ma, J., Zhou, J. and Fang, Y. (2016). Sustainability development strategy of China's high speed rail. *Journal of Zhejiang University-SCIENCE A*, [online] 17(12), pp.923-932. Available at: https://link.springer.com/chapter/10.1007/978-981-10-5610-9_1 [Accessed 2 Dec. 2019].

Tendersinfo.com. (2019). [online] Available at: http://www.tendersinfo.com/blogs/germanys-railway-sector-on-the-rise/ [Accessed 14 Aug. 2019].

The Economic Times. (2019). *China to increase high-speed rail network to 30,000 km by 2020*. [online] Available at: https://economictimes.indiatimes.com/news/international/business/china-to-increase-high-speed-rail-network-to-30000-km-by-2020/articleshow/51922944.cms [Accessed 1 Sep. 2019].

The Geography of Transport Systems. (2019). *Rail Track Mileage and Number of Class I Rail Carriers, United States, 1830-2016*. [online] Available at: https://transportgeography.org/?page_id=1954 [Accessed 9 Aug. 2019].

The Independent. (2019). *Global temperatures could rise by 6C by 2100, with unimaginable consequences*. [online] Available at: https://www.independent.co.uk/environment/climate-change/global-warming-experts-say-temperatures-could-rise-by-6c-by-2100-with-cataclysmic-results-10193506.html [Accessed 13 Aug. 2019].

Thelocal.es. (2019). *Spain greets record 64.9 million tourists in 2014*. [online] Available at: http://www.thelocal.es/20150122/tourism-record-visitors-to-spain-top-65-million [Accessed 14 Aug. 2019].

Thenbs.com. (2019). *POS Planning for accessible and sustainable transport, Town and Country Planning Association - Publication Index | NBS*. [online] Available at: https://www.thenbs.com/PublicationIndex/documents/details?DocId=290584 [Accessed 13 Aug. 2019].

The Royal Society (1995) "The Railways, Challenges to Science and Technology". London.
pp 11-33.

Thsrc.com.tw. (2019). *Taiwan High Speed Rail, 2017 Annual REport*. [online] Available at: http://www.thsrc.com.tw/event/tmp/pdf/2017_annual_EN.pdf [Accessed 23 Oct. 2019].

Times, E.H. (2016), *About the redevelopment of king's cross*. Available at: https://www.kingscross.co.uk/development [Accessed 23 October 2016].

Topham, G. and Farrell, S. (2016) *Eurotunnel claims compensation for migrant disruption*. Available at: https://www.theguardian.com/business/2016/feb/18/eurotunnel-claims-compensation-for-migrant-disruption [Accessed 12 January 2017].

Transport-exhibitions.com. (2019). *Turkey and Eurasia | ITE Transport & Logistics*. [online] Available at: http://www.transport-exhibitions.com/Market-Insights/Turkey-and-Eurasia [Accessed 9 Aug. 2019].

Transport policy and the environment. (1990). Paris: European Conference of Ministers of Transport, pp.120-121, 131.

Tsp-data-portal.org. (2019). *Breakdown of Electricity Generation by Energy Source | The Shift Project Data Portal*. [online] Available at: http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart [Accessed 8 Aug. 2019].

Tuler, M. and Kaewunruen, S. (2017). Life cycle analysis of mitigation methodologies for railway rolling noise and groundbourne vibration. *Journal of Environmental Management*, [online] 191, pp.75-82. Available at: https://www.sciencedirect.com/science/article/pii/S0301479716310684 [Accessed 2 May 2018].

Tunnelsonline.info. (2019). *Lyon-Turin work forges ahead despite violence - Tunnels & Tunnelling International*. [online] Available at: http://www.tunnelsonline.info/news/lyon-turin-work-forges-ahead-despite-violence [Accessed 9 Aug. 2019].

Tunneltalk.com. (2019). *Governor signs California HSR funding bill*. [online] Available at: https://www.tunneltalk.com/California-high-speed-rail-July12-Governor-signs-HSR-funding-bill.php [Accessed 14 Aug. 2019].

Ub.edu. (2019). [online] Available at: http://www.ub.edu/irea/working_papers/2015/201527.pdf [Accessed 14 Aug. 2019].

UIC, CER (2015) *Rail transport and environment: Facts & figures*. Available at: http://www.cer.be/sites/default/files/publication/Facts%20and%20figures%202014.pdf [Accessed 22 December 2016].

Uic-environment.org. (2019). *Workshops - UIC Sustainable Development Conference 2016*. [online] Available at: http://uic-environment.org/workshops [Accessed 3 August 2019].

UIC - International union of railways. (2019a). *High-Speed - UIC - International union of railways*. [online] Available at: http://www.uic.org/highspeed#What-is-High-Speed-Rail [Accessed 3 August 2019].

UIC - International union of railways. (2019b). *High-Speed Rail History - UIC - International union of railways*. [online] Available at: https://uic.org/High-Speed-History#t1964-1981-The-birth-of-the-TGV [Accessed 4 Aug. 2019].

UIC - International union of railways. (2019c). *Energy and CO2 emissions - UIC - International union of railways*. [online] Available at: https://uic.org/sustainable-development/energy-and-co2-emissions/ [Accessed 8 Aug. 2019].

UIC - International union of railways. (2019d). *High-Speed Database & Maps - UIC - International union of railways*. [online] Available at: https://uic.org/high-speed-database-maps#&gid=1&pid=8 [Accessed 8 Aug. 2019].

Uic.org. (2018a). *World High Speed Rolling Stock*. [online] Available at: https://uic.org/IMG/pdf/20180401_high_speed_rolling_stock.pdf [Accessed 30 April 2018].

Uic.org. (2018b). [online] Available at: http://uic.org/IMG/pdf/facts_and_figures_2014_v1.0-4.pdf [Accessed 3 August 2018].

Uic.org. (2019). [online] Available at: https://uic.org/IMG/pdf/high_speed_passenger-km_20171130_.pdf [Accessed 7 Aug. 2019].

Uic.org. (2019b). [online] Available at: https://uic.org/IMG/pdf/report_rolingstock__final__en.pdf [Accessed 7 Aug. 2019].

Uic.org. (2019c). [online] Available at: https://uic.org/IMG/pdf/20181001-high-speed-lines-in-the-world.pdf [Accessed 8 Aug. 2019].

Uic.org. (2019d). [online] Available at: https://uic.org/IMG/pdf/railway_noise_in_europe_2016_final.pdf [Accessed 8 Aug. 2019].

Uic-stats.uic.org. (2019). *RAILISA STAT UIC*. [online] Available at: https://uic-stats.uic.org/list/ [Accessed 21 Aug. 2019].

UN CC:Learn. (2019). *Climate Change and Tourism: Responding to Global Challenges | UN CC:Learn*. [online] Available at: https://www.uncclearn.org/learning-resources/library/1876 [Accessed 15 Aug. 2019].

Unfccc.int. 2020. [online] Available at: <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement> [Accessed 21 March 2020].

unife.org. (2013). *Recyclability and Recoverability Calculation Method, Railway Rolling Stock*. [online] Available at: http://unife.org/component/attachments/?task=download&id=326 [Accessed 12 Jul. 2017].

U.S. (2019). *LPC-Taiwan's High Speed Rail Corp's lenders agree restructuring plan*. [online] Available at: https://www.reuters.com/article/taiwan-rail-loan/lpc-taiwans-high-speed-rail-corps-lenders-agree-restructuring-plan-idUSL5N10G2JZ20150805 [Accessed 23 Oct. 2019].

Ushsr.com. (2019). *Sustainability & High-Speed Rail*. [online] Available at: http://www.ushsr.com/benefits/sustainability.html [Accessed 3 August 2019].

Uysal, O. (2019a). *High speed train projects slow down*. [online] Rail Turkey En. Available at: https://railturkey.org/2017/04/06/high-speed-train-projects-slow-down [Accessed 9 Aug. 2019].

Uysal, O. (2019b). *Every one of four traveled fast*. [online] Rail Turkey En. Available at: https://railturkey.org/2016/08/14/every-one-of-four-traveled-fast/ [Accessed 9 Aug. 2019].

Uysal, O. (2019c). *High speed lines of Turkey – The complete guide*. [online] Rail Turkey En. Available at: https://railturkey.org/2015/06/17/the-whole-high-speed-lines-of-turkey/ [Accessed 9 Aug. 2019].

Vardar, T., Altan, M. and Naimi, S. (2017). Economic and Technological Evaluation of Transportation System, New Trends. *Journal of Sustainable Construction Materials and Technologies*, 1(1), pp.83-88.

Vialibre-ffe.com. (2019). [online] Available at: http://www.vialibre-ffe.com/pdf/lineas_altavelocidad_mundo.pdf [Accessed 3 August 2019].

Vos, P. (2016). *Railway Noise in Europe-State of the Art Report*. [online] Uic.org. Available at: https://uic.org/IMG/pdf/railway_noise_in_europe_2016_final.pdf [Accessed 21 May 2018].

Wang, Y. and Lan, Y. (2013). Estimating most productive scale size with double frontiers data envelopment analysis. *Economic Modelling*, [online] 33, pp.182-186. Available at: https://www.sciencedirect.com/science/article/pii/S0264999313001521 [Accessed 6 Aug. 2019].

Watanabe, M. and Tanaka, K. (2007). Efficiency analysis of Chinese industry: A directional distance function approach. *Energy Policy*, [online] 35(12), pp.6323-6331. Available at: https://www.sciencedirect.com/science/article/pii/S030142150700328X [Accessed 6 Aug. 2019].

Waters, L., Wilkes, E. and Goodright, V. (2015). *Energy Consumption in the UK (2015)*. [online] Available at: https://archive.uea.ac.uk/~e680/energy/energy_links/statistics/UK-Energy/ECUK_Chapter_2_-_Transport_factsheet.pdf [Accessed 12 July 2017].

Watson, I. (2016) *External Costs Affected Sustainability of Transport Systems.* Available at: [Accessed 12 July 2017].

Watson, I., Ali, A. and Bayyati, A. (2017a). *Investigation of the operational reliability of high-speed railways and possible measures of improvement.* In: *Railway Engineering Conference 2017*. Edinburgh: University of Edinburgh.

Watson, I., Ali, A. and Bayyati, A. (2017b). *Social Sustainability of HSR-Comparative Study*. In: *Stephenson Conference 2017*. London: IMechE.

Watson I., Ali A., Bayyati A., (2017c) "*Sustainability of HSR as a Mass Transportation Mode in terms of Efficient use of Natural Resources*", International Congress on High-Speed Rail: Technologies and Long-Term Impact, 2017, Ciudad Real, Spain, University de Castilla-La Mancha, 4-6 October 2017 Available at: https://eventos.uclm.es/7333/section/5606/international-congress-on-high-speed-rail_-technologies-and-long-term-impacts.html

Watson, I., Ali, A. and Bayyati, A. (2019). Sustainability of HSR-Comparative Study. *Transport*, [online] 172(1). Available at: https://www.icevirtuallibrary.com/doi/abs/10.1680/jtran.18.00131 [Accessed 20 Oct. 2019].

Watson, R. (2012). *Factors Influencing the Energy Consumption of High Speed Rail and Comparisons with other Modes*. [online] Available at: https://spiral.imperial.ac.uk:8443/bitstream/10044/1/11653/1/Watson-R-2012-PhD-Thesis.pdf [Accessed 12 July 2017].

Wdi.worldbank.org. (2019). *World Development Indicators | The World Bank*. [online] Available at: http://wdi.worldbank.org/table/WV.1 [Accessed 21 Aug. 2019].

WEG. (2019). *Página não encontrada | WEG*. [online] Available at: http://www.weg.net/institutional/GB/en/news/products-and-solutions/powering-the-world-s-largest-industrial-shredder [Accessed 3 August 2019].

weg.net. (2009). *Powering the World's Largest Industrial Shredder*. [online] Available at: http://www.weg.net/institutional/GB/en/news/products-and-solutions/powering-the-world-s-largest-industrial-shredder [Accessed 12 Jul. 2017].

Welle, D. (2001) *Deutsche Bahn to publish monthly punctuality statistics online | business | DW.COM | 03.08.2011*. Available at: http://www.dw.com/en/deutsche-bahn-to-publish-monthly-punctuality-statistics-online/a-15277541 [Accessed 12 January 2017].

Whitelegg, J. (1994). *Transport and Land Take*. [online] Available at: http://www.eco-logica.co.uk/pdf/CPRELandTake.pdf [Accessed 12 July 2017].

Whitelee, J. and Haq, G. (2003a). *The earthscan reader on world transport policy and practice*. London: Earthscan publications, p.5,11.

Whitelegg, J. and Haq, G. (2003b). *World Transport*. London: Earthscan Publications Ltd, pp. 5,19.

Wolf, S. (2010). *California High-Speed Train Project*. [online] Hsr.ca.gov. Available at: http://www.hsr.ca.gov/docs/programs/eir_memos/Proj_Guidelines_SoundFactSht.pdf [Accessed 30 April 2018].

World Bank (2018), A *tool to measure the regional economic impacts of china's high speed rail*. Available at: http://www.worldbank.org/en/news/press-release/2014/07/29/a-tool-to-measure-the-regional-economic-impacts-of-china-high-speed-rail [Accessed 23 October 2018].

World Bank. (2019). *Cost of High Speed Rail in China One Third Lower than in Other Countries*. [online] Available at: http://www.worldbank.org/en/news/press-release/2014/07/10/cost-of-high-speed-rail-in-china-one-third-lower-than-in-other-countries [Accessed 9 Aug. 2019].

World Economic Forum. (2019). *Does high-speed rail benefit business?*. [online] Available at: https://www.weforum.org/agenda/2014/09/high-speed-rail-supply-networks-firm-performance/ [Accessed 7 Aug. 2019].

Worldometers.info. (2018). *Population by Country (2018) - Worldometers*. [online] Available at: http://www.worldometers.info/world-population/population-by-country/ [Accessed 30 April 2018].

Worldpopulationreview.com. (2019). [online] Available at: http://worldpopulationreview.com/countries/japan-population/ [Accessed 7 Aug. 2019].

Worldpopulationreview.com. (2019b). [online] Available at: http://worldpopulationreview.com/countries/china-population/ [Accessed 9 Aug. 2019].

Worldpopulationreview.com. (2019). [online] Available at: http://worldpopulationreview.com/countries/turkey-population/ [Accessed 9 Aug. 2019].

Yu, M. (2008). Assessing the technical efficiency, service effectiveness, and technical effectiveness of the world's railways through NDEA analysis. *Transportation Research Part A: Policy and Practice*, [online] 42(10), pp.1283-1294. Available at: https://www.sciencedirect.com/science/article/pii/S0965856408000918 [Accessed 6 Aug. 2019].

Yu, M. and Fan, C. (2009). Measuring the performance of multimode bus transit: A mixed structure network DEA model. *Transportation Research Part E: Logistics and Transportation Review*, [online] 45(3), pp.501-515. Available at:

https://www.sciencedirect.com/science/article/pii/S1366554508001294 [Accessed 6 Aug. 2019].

Yu, M. and Lin, E. (2008). Efficiency and effectiveness in railway performance using a multi-activity network DEA model. *Omega*, [online] 36(6), pp.1005-1017. Available at: https://www.sciencedirect.com/science/article/pii/S0305048307000916 [Accessed 4 Aug. 2019].

Yu, Y. and Wen, Z. (2010). Evaluating China's urban environmental sustainability with Data Envelopment Analysis. *Ecological Economics*, [online] 69(9), pp.1748-1755. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0921800910001497?via%3Dihub [Accessed 11 Dec. 2019].

Zhang, J., Xiao, X., Sheng, X., Zhang, C., Wang, R. and Jin, X. (2016). SEA and contribution analysis for interior noise of a high-speed train. *Applied Acoustics*, [online] 112, pp.158-170. Available at: https://www.sciencedirect.com/science/article/pii/S0003682X16301414 [Accessed 1 May 2018].

Zhang, N., Zhou, P. and Kung, C. (2015). Total-factor carbon emission performance of the Chinese transportation industry: A bootstrapped non-radial Malmquist index analysis. *Renewable and Sustainable Energy Reviews*, [online] 41, pp.584-593. Available at: https://www.sciencedirect.com/science/article/pii/S136403211400762X [Accessed 6 Aug. 2019].

Zhang, X. (2010). The directivity of railway noise at different speeds. *Journal of Sound and Vibration*, [online] 329(25), pp.5273-5288. Available at: https://www.sciencedirect.com/science/article/pii/S0022460X10004384 [Accessed 1 May 2018].

Zhang, X. and Jonasson, H. (2006). Directivity of railway noise sources. *Journal of Sound and Vibration*, [online] 293(3-5), pp.995-1006. Available at: https://www.sciencedirect.com/science/article/pii/S0022460X05007972 [Accessed 1 May 2018].

Zhang, X., Song, H. and Huang, G. (2019). *Tourism supply chain management: A new research agenda*. Available at:http://www.thetravelfoundation.org.uk/images/media/5_tourism_supply-chains.pdf [Accessed 14 Aug. 2019].

Zhou, H., Yang, Y., Chen, Y. and Zhu, J. (2018). Data envelopment analysis application in sustainability: The origins, development and future directions. *European Journal of Operational Research*, [online] 264(1), pp.1-16. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221717305623 [Accessed 4 Aug. 2019].

Zhou, L. and Shen, Z. (2011). Progress in high-speed train technology around the world. *Journal of Modern Transportation*, [online] 19(1), pp.1-6. Available at: https://link.springer.com/article/10.1007/BF03325733 [Accessed 9 Aug. 2019].

Zhou, P., Poh, K. and Ang, B. (2007). A non-radial DEA approach to measuring environmental performance. *European Journal of Operational Research*, [online] 178(1), pp.1-9. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377221706003407 [Accessed 6 Aug. 2019].

Zhu, J. (2015). *Data envelopment analysis*. Boston, Mass: Springer, pp 34-38

Appendix A

Detailed information on HSR systems in selected countries

A.1 HSR in Japan

The first high speed line was opened in Japan on 1 October 1964. It took five years to construct a 515km line between Tokyo and Osaka. It gave a tremendous boost to the economy in Japan and encouraged countries around the world to develop HSR in their own countries. The population of Japan is 127.3 million and a half of the population are in the corridor between Tokyo and Osaka where also two-thirds of the national industry is based (Worldpopulationreview.com., 2019). The high-speed line from Tokyo to Osaka is the most successful line in the world (network and calculator, 2019). Japan has 3041km of HSR in operation, 402km under construction, and there are plans to build another 194km. (Uic.org., 2019). Japan is the second, after China, for the largest high-speed train network in operation, followed by Spain, France, and Germany (Uic.org.,2019).

The core of the success of the Shinkansen (a network of high-speed lines in Japan) lies in the decision to build dedicated lines for high-speed trains. Before the decision had been taken a few other options were discussed. First, the size of gauge for the track that would be used: Japanese-gauge (1067mm) or standard-gauge (1435mm), second, build the HSR alongside the existing line or develop a new corridor. Behind the reason to build the line in a new corridor was that the existing line had too many sharp curves for the high-speed trains (Japanese Railway Technology Today, 2001).

Another reason was that the new track layout would affect many people, as the area along the railway line is densely populated. At the end, it was decided to provide a new double track high-speed standard-gauge line for speeds up to 250kph. It was innovative to operate commercial services at this speed. Because of geological and geographical conditions in Japan, HSR requires many long tunnels and bridges. The disadvantage of this decision was the very expensive civil engineering work, approximately 13% (86km) of the line is in tunnels, and 33% (174km) on bridges and viaducts (Japanese Railway Technology Today, 2001). HSR infrastructure in Japan must be resistant to earthquakes, floods and deep snow.

To run the high-speed trains on the new line, the AC electrification system has been used. As this line was new, it was simple to provide overhead wires from the beginning. Majority of electricity that is used on Japan railways is the same as in France which comes from nuclear power stations. After 11 March 2011 when the Fukushima reactor went into meltdown, energy policy was reviewed and now Japan as most developed countries worldwide is concentrating on developing renewable energy.

From the beginning of building Shinkansen, it was decided not to use outside signals to provide information for the driver but to provide indications inside the cabin. It was achieved by transmitting coded signals to the train through track circuits and receivers installed at intervals along the track. In-cab signalling is mandatory today for all high-speed systems around the world. For dedicated high-speed lines today, continuous control systems such as ATC in Japan, TVM in France and LZB in Germany is applied (Ltd, 2019). The track of Shinkansen was divided in sections, and if only one section ahead is clear, the train can move forward. This means that the train ahead was only one block away. In this case the train can move only with reduced speed and if the train ahead is two or more blocks ahead, then the train behind can move on at full speed (Japanese Railway Technology Today, 2001). This system increases the capacity of a track.

Along with the new infrastructure, there is also a new generation of a train that has been built. One innovation of the Shinkansen rolling stock was that instead of putting traction equipment in a locomotive, it was spread along the length of the train. This reduces the maximum axle-load to 16tons (Japanese Railway Technology Today, 2001). This increases the speed of the train, minimises the infrastructure maintenance, and reduces energy consumption. Articulated with distributed power trains have the lowest axle load. However, with distributed power, the noise in passenger saloons is higher than with concentrated power (locomotive) trains (Uic.org., 2019).

Improving acceleration can reduce travel time without increasing the speed of the train. Some high-speed trains travel only short distances between stops, they need high acceleration and quick deceleration. On the Tokyo-Osaka section (515km), there are 17 stations approximately 50km between them, but on the Paris-Lyon section (389km) there are only two stations and most of the TGV trains do not stop (Japanese Railway Technology Today, 2001). Good acceleration and deceleration performance can noticeably reduce travel time, particularly for trains running short distances.

In 1964 it took four hours to get from Tokyo to Osaka by 2007 it reduced the time to 2 hours 25 minutes after speeds were increased to 285kph (Ipfs.io., 2019). In 2015, the number of departures of the Shinkansen bullet from Tokyo have increased to 14 times per hour (358 departures per day) and daily ridership increased to 445000 with an average delay per train of 0.2 minutes. Totally 355 million passengers use a high- speed railway every year. On average, a train has 1323 seats that are much more seats per train than in Germany or France. This is one reason for the profitability of the Shinkansen (Scribd., 2019). Figure A.1 shows the plan of the Shinkansen HSR lines in Japan.

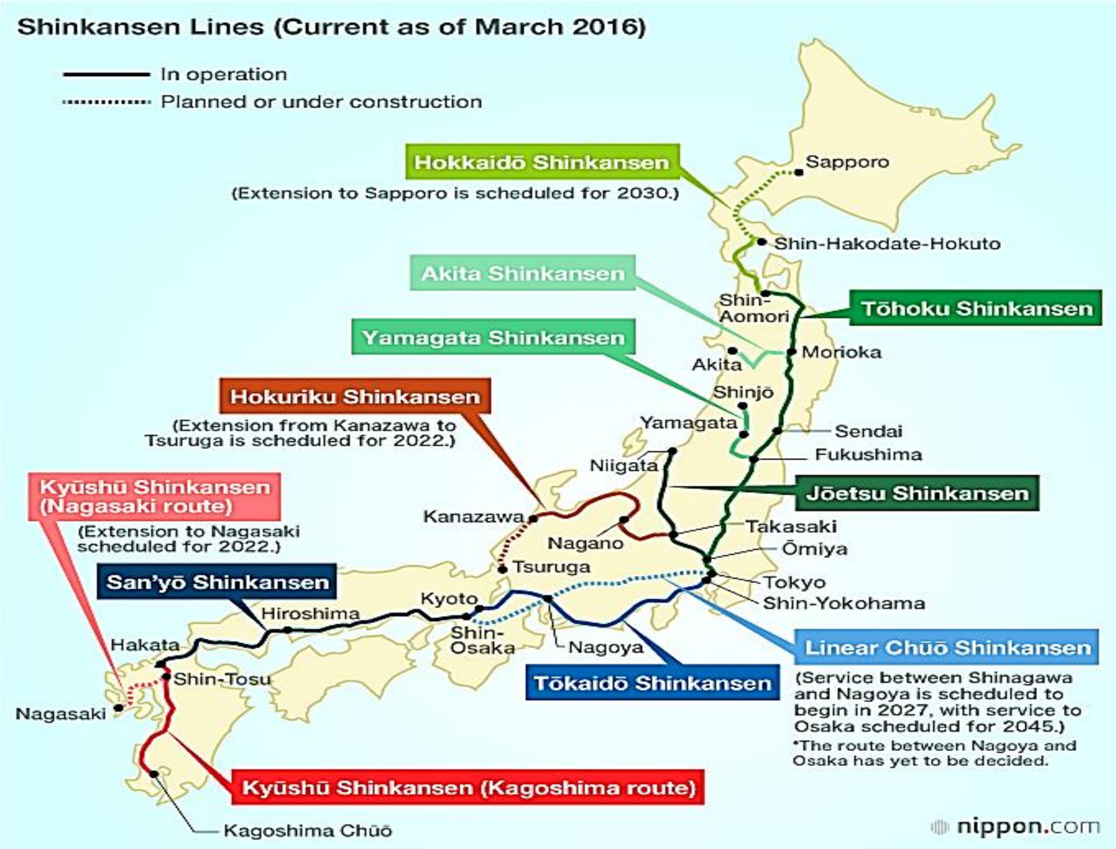

Figure A.1 Japan's HSR System in 2016 (Source: nippon.com., 2019)

There is no plan to increase the speed on the Tokaido-Shinkansen line. The line originally had been designed for lower speeds that can be achieved by the new generations of high-speed train. Having fewer trains with very high speeds, it would be difficult to fit all the existing slower trains in a timetable. Also, the tracks lay in an area with a high-density population and with very strict environmental constraints. With the increase in speed it increased the level of noise and vibration. One of the solutions to be found was to make trains lighter and smaller. Another solution is to reduce the noise level from pantographs and bogies. Japan was the first country to set environmentally acceptable noise levels for high-speed trains.

In 1964 when Shinkansen was introduced, the noise level for rolling stock at speeds up to 210kph was 90dB(A), by increasing the speed to 300kph in 1997 the noise level was no higher than 75d(B)A (Japanese Railway Technology Today, 2001). This was achieved by developing a low-noise pantograph, reducing the aerodynamic noise by improving the rolling stock exterior. Also, in some places 2-metre-high sound-absorbing barriers had been installed (Japanese Railway Technology Today, 2001).

An additional problem was the high noise level that came at the exit of the tunnels with a length of 1500 metres and above. Shinkansen lines have 86km of tunnels and when trains pass through long tunnels, the windows, and doors of houses along the track vibrate. This vibration was caused by micro-pressure waves which sound like an explosion when trains exit from a tunnel (Japanese Railway Technology Today, 2001).

The highest level of noise is near tunnels with slab track and lowest near tunnels with ballast track. Shinkansen was a great economic success, and it is a big engineering achievement and other countries worldwide started to look to developing HSR systems too. With reducing journey time, railways become more attractive to customers. To increase the capacity of trains in Japan, they developed wide bodied double deck trains (Figure A.2) and the restaurant car abandoned.

The safety records and punctuality on Shinkansen lines are outstanding. The HSR carried out over thousands of scheduled journeys per day and the average delay across all high-speed lines is 0.2 minutes per train, including weather related delays. For over 50 years of operation and carrying over 10 billion passengers without an accident in which passengers could be killed or injured, Shinkansen trains are the most safe and reliable in the world. The new generation of Shinkansen trains N700S have a very advanced braking system, emergency braking can stop a train moving at a top speed of 285kph at a stopping distance of 2.8km (International Railway Journal, 2019). Figure A.2 shows a cross section of Japanese N700-I and European high-speed trains. On average, trains in Asia have twice as many seats than trains in Europe.

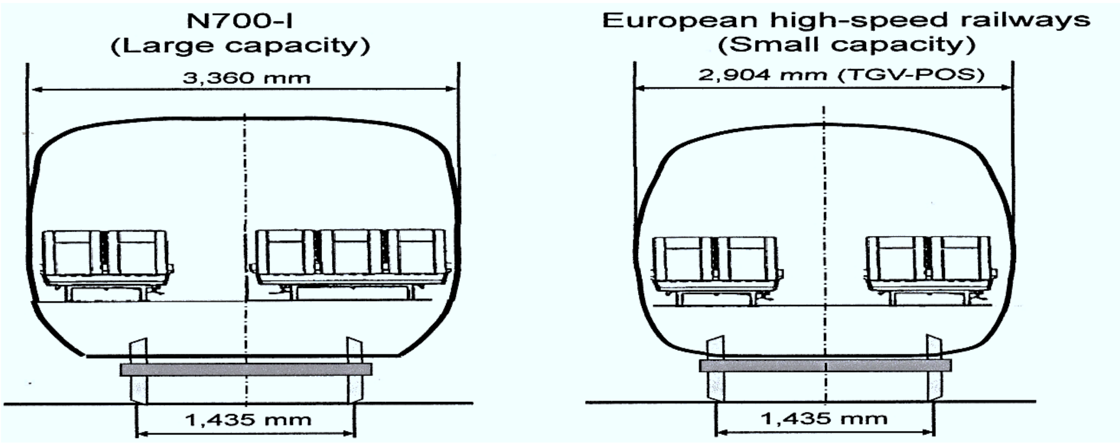

Figure A.2 Comparison of cross sections of Japanese N700-I and European high-speed train (Source: Amended from www. jterc.or.jp)

N700 is one of the latest Shinkansen trains that can be formed from 8 cars with a capacity of 636 seats. High-speed trains in Japan have rotating seats that can be rotated automatically from the driver's cab at the departure station to face how the train will be travelling. Passengers prefer to sit facing the way they are going. The maximum length of trains in Japan is the same as in Europe, which is 400 metres. In Japan High Speed Rolling Stock (HSRS) was designed for a 15-20-year life cycle, but in Europe it is around 30 years (Uic.org., 2019b), and because of this HSRS in Japan do not need to for major renovation or technological innovations within their life cycle. This is an example and a good balance between economic benefits, shorter asset life and low maintenance costs.

Shinkansen is the great economic success of Japan, and today the Shinkansen has an operational revenue of around $19 billion a year (ISO, 2019). This success has many reasons, and one of them is that the railway company owns the entire infrastructure, stations, the rolling stock, the track, and land around the railways. There is less bureaucracy, less management and decisions are taken more quickly. With the future decline in Japan's population from the current 127 million possible to 96 million by 2050 (Worldpopulationreview.com., 2019) there will be a slowdown in new developments of HSR, as there will not be enough demand for high-speed trains.

A.2 HSR in France

High-speed trains were introduced in France over three decades ago in 1981, and they have carried over 2 billion passengers during these years (Electric-rly-society.org.uk., 2019). It was an immediate successful implementation of TGV. It caused a decrease in air and road traffic, especially for flights. TGV offered a shorter trip time, higher comfort, frequent services, and competitive prices.

France has 450 TGV trains and they are serving around 230 destinations; operating in France and outside: to Belgium, Germany, Spain, Italy, Luxembourg, and Switzerland (International Railway Journal, 2019b). Around 130 million passengers use the HSR in France every year (International Railway Journal, 2019c). From the beginning, the French railways had a very substantial government investment, and it was the government's determined ambition to build a railway corridor to connect the south of France with Paris.

This corridor, Paris to Marseille via Lyon is the most important one in France and serves around 40% of the population. The demand for travel between Paris and the South of France was so high that existing infrastructure could not satisfy it. The development of the HSR network around Paris, which connects Paris with other capitals of Europe, was more a result of political reasoning than market needs.

However, after 33 years of operating high-speed trains in France, almost 40 percent of these trains travel on conventional track (International Railway Journal, 2019b). Around 60 percent of TGV trains are travelling on new lines designated only for TGV and all other traffic was prohibited. The new lines have higher gradients unsuitable for freight traffic. In France, the new HSR's were designed to avoid tunnelling, and this gives the benefit of the possibility to implement the double deck trains. The TGV Duplex was introduced in 1996, this train can travel at speeds up to 300 kph (Railway Technology, 2019d). The big achievement of the HSR system in France is that the TGV system is compatible with existing conventional railways.

National Society of French Railways (SNCF) has one of the fastest train services in the world. In April 2007, a TGV test train reached 574.8kph. The latest TGV Duplex Oceane trains have a maximum operational speed of 320kph and they comprise two powered cars one at each end and eight carriages with a capacity of 556 seats, with the same amount of staff on the train as the TGV. The length of TGV Duplex is 200 meters. These two trains can be coupled together to increase the capacity of the train on busy lines (Uic.org., 2018).

There are two different ways to power high-speed trains: it can be as in Japan, with distributed traction, or as in France, with TGV, centralized traction. With increasing awareness about the damaging effect caused by transport on the environment and looking for ways to increase efficiency of transport it looks more economically appropriate to use distributed traction to power high-speed trains.

There are other ways to increase the capacity of trains and one of them can be double-deckers (France, Germany, and Japan) or the widening of carriages (Sweden, Japan). Increasing the capacity of trains gives the possibility to reduce operational costs, and this can reduce the railways' fares. To increase capacity of railway lines it is needed to electrify the line, implement more advanced signalling systems, increase speed of trains, and have dedicated lines for high-speed trains only.

One of the most important developments in the construction of TGV-PSE was the introduction of articulated suspension between passenger vehicles. Using this innovation, it can reduce the weight of the train, reduce the aerodynamic drag, decrease the level of noise from the train, and improve passenger comfort. Figure A.3 shows non-articulated and articulated bogies that used by HS Rolling Stock (RS).

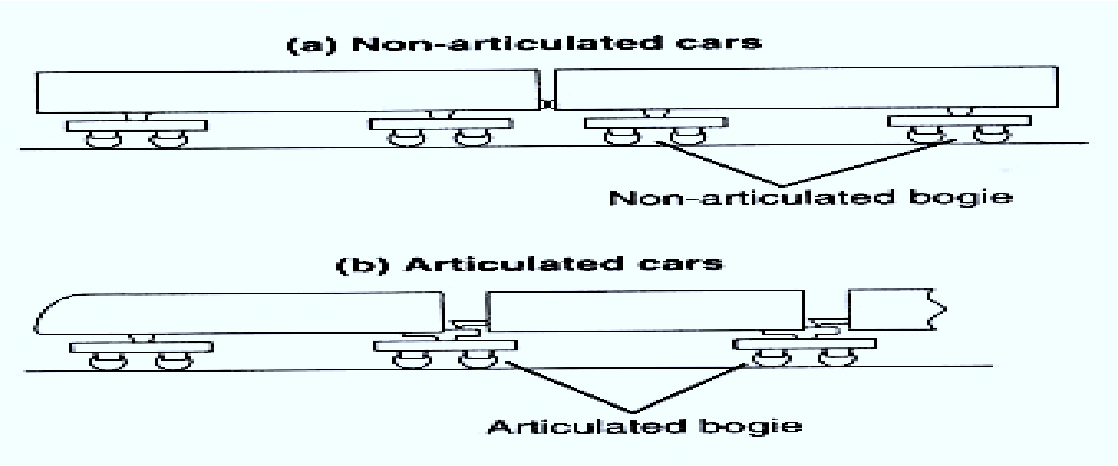

Figure A.3 Non-articulated and articulated bogies (Source: Japanese Railway Technology Today)

A traditional coach has two bogies, and each bogie has two axles; on TGV-PSE coaches each bogie supports two coaches. Advantages of articulated trains are a more comfortable ride, passengers on the train are less affected by running noise, but the downside of articulated trains are increased axle load and maintenance of these bogies are more difficult. TGV uses the 25kV AC electrification system, but it can also work on 1,500 DC. All TGV trains have at least two electrification systems. To extend track formation life and increase the speed of trains, the weight on 1 axle was restricted to 17 tons (Uic.org., 2018). Minimizing the axle load will reduce infrastructure and other structural maintenance, reduce the construction costs, and reduce the noise level.

The safety of passengers for any railway network is a crucial requirement. To improve the safety of high-speed trains in France, the lines were redesigned without level crossings, also lines were fully fenced, and advanced equipment was fitted to detect obstructions that occur on a railway line. Unfortunately, a fatal accident happened on 19 November 2015 during a TGV test run. The accident left 11 people fatally injured and 37 in a serious condition. Speeding caused this accident. The design limits were set for that point of line 176kph, but the train was travelling at a speed of 265kph (NewsComAu., 2019). In the last few years, the increasing amount of accidents on high-speed lines (Spain, China, and France) makes people cautious about the level of safety on high-speed trains.

From 2008 the profitability of TGV steadily declined, and it was pronounced that there was a need to reduce several stations served by TGV to make HSR network profitable. HSR services carry only 7% of passengers, but accounts for 61% of the total French rail network traffic. In France, high-speed trains serve 230 stations (International Railway Journal, 2019b).

There has been a lot of pressure from local governments to open more stations, and in this case the HSR in France lost the aim of high-speed trains, which is to connect only high-density populated centres with frequent services and only with a few stops. Since the economic crisis in 2007, the number of passengers using the high-speed trains continues to decline, also operation margins fell from 29% in 2008 to 12% in 2013, and new lines are now not as profitable as had been predicted. For example, TGV Nord has only 5% profitability, but was forecasting 20% (International Railway Journal, 2019b).

One of the best characteristics of HSR lines in France is the low construction cost. The first railway line between Paris and Lyon cost around $4 million per km (Watson et al., 2019). At the design stage of HSR in France was decided that HSR lines will be used only by high speed trains, but upgraded and conventional tracks will be used by high speed trains and conventional trains. Figure A.4 shows the operating and maintenance costs for motorway and HSR in France and Spain.

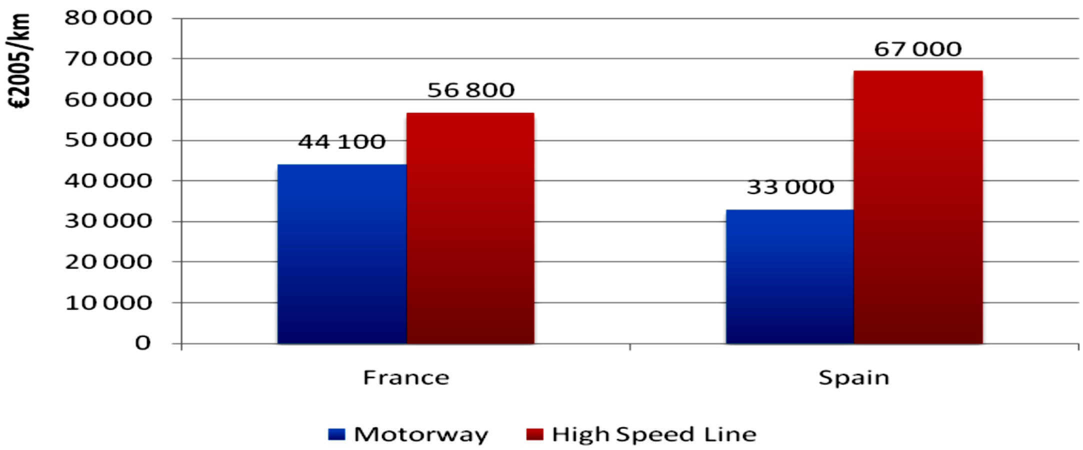

Figure A.4 Operating and maintenance costs for HSR in France and Spain (Source: Jehanno et al., 2011)

Operating and maintenance costs in Spain are slightly higher than in France, and one reason would be that the Spanish railway network has two different sizes of gauge and two electrification systems. This will affect the costs of maintenance. The new generation of TGV trains are lighter, have a 15% lower energy consumption and designed to be 98% recyclable with the maximum speed of 360km/h. (Jehanno et al., 2011). Reducing the weight has been achieved by using aluminium instead of steel and by using articulated bogies. The train has a regenerative braking system which recovers 8MV of electricity and puts it back in the network, it sufficiently reduces the CO_2 emissions and increases the efficiency of high-speed trains.

TGV trains have been installed with Automatic Protection System (APS) and been fitted with in-cab signalling system TVM430. The tracks have been divided into 1,500 metres section and the in-cab signalling system TVM430 informs the driver of the maximum speed possible on any section. If the train's current speed is higher than the speed limit for that section, then ATP applies the brakes automatically. The TVM430 signalling system allows three minutes headway, and this increases the capacity of track to twenty-two thousand passengers in one hour in one direction (Railway Technology, 2019e). This capacity of rail track is equal to a six-lane motorway.

In 2017 in France there was 2814km HSR lines in operation and there are plans for more to be built. All existing HSR lines are interconnected. TGV is the great technological achievement, and France would like to continue to expand the HSR system. However, in the last thirty years, there have not been enough funds to upgrade conventional rail and at this moment SNCF has a dilemma either to upgrade the conventional network or continue to build TGV lines. In 2017, the structural losses of the Infrastructure Division SNCF reached €46.6bn (Ltd, 2019b). In this condition, SNCF has announced that they will not replace TGV stock until it reaches the age of 40 years.

Most of HSR's around the world are not profitable but need to look what benefit they can bring in areas where they pass through and one example of this can be the city of Lille. Lille is in the north of France near the border with Belgium. It is a good example of how a city can flourish from the bypassing of high-speed trains. With the development of the TGV HSR and TGV station, it brought prosperity to the city, blooming commercial activities, and tourism.

The high-speed trains are the most efficient mode of transport. This is one reasons that society continues to fund HSR services. HSR gives time saving, energy saving, improves accessibility, increases economic activity, and generates employment. However, with a low-density population in France and only a few larges populated urban areas, it looks unlikely that in the current condition the HSR will be profitable.

A.3 HSR in Spain

Construction of the HSR in Spain began in 1989 in the corridor between Madrid and Seville, and high-speed trains (AVE) started to run in 1992. Spain's HSR network is one of the widest in the world. In 2018, the length of the HSR network was 2852km and 904km were under construction. Spain is planning to build another 1061km, with an average cost of €14m per kilometre. Only China and Japan have more kilometres of HSR lines (Uic.org., 2019c). HSR in Spain has a fleet of 229 trains with an average age of 11 years and in 2015 carried over 35 million passengers (International Railway Journal, 2019d).

The Spanish HSR has a standard gauge of 1435mm and electrified with 25 kV AC and represents 16% of the total Spanish network. However, HSR consumed around 25% of the total amount of electricity consumed by Spanish railways. The conventional line has an Iberian gauge 1668mm and electrified with 3kV DC or 1,5kV DC from overhead wires (Events.uic.org., 2019). Higher voltage means that there are less frequent losses during the transformation and transmission processes. For the AC electrification system, there is a need to produce an 8.8% additional amount of energy but for DC 22.6%. Figure A.5 shows the HSR network in Spain in 2015.

Figure A.5 HSR network in Spain (Source: UIC - International union of railways., 2019d).

This amount of energy must be produced on top of the amount consumed by the pantograph (UIC - International union of railways, 2019c). One advantage of 25kV AC is the possibility to supply power to high-speed trains with a greater distance between sub stations (approximately 50km apart), which means reduced construction and maintenance costs. In Spain, they have 59 AC substations and 384 DC substations (Events.uic.org., 2019). High-speed trains can be run on 100% electric power and it is the only one mode of transport that need not have additional investments to shift from fossil fuels to renewable energy. In Spain, around 50% of the electricity used by these trains comes from renewable sources (Tsp-data-portal.org., 2019).

The success of HSR around Europe is in part because of the interoperability with existing lines (France and Germany), but in Spain this is not the case. Conventional lines in Spain have a gauge of 1668mm. The difficulty of the Spanish railway network is that it has two different sizes of rail line gauges: standard gauge (1435mm) and Iberian gauge (1668mm). Some new lines are being constructed to allow trains with standard and Iberian gauge wheels to run on the same track. Talgo trains have an automatic gauge changing equipment which allows for the change from one type of gauge to another without stopping at speeds up to 15kph and have operational speeds 220kph (Shael, 2019). Another reason HSR was such a big success in Europe is that trains provide reliability and comfort.

Compared with other modes of transport, passengers on trains can be highly productive. High-speed trains offer free internet, live TV, the possibility of use of mobile telephones, carriages provided with power sockets for charging computers and telephones and overall passengers have a reliable and comfortable journey. In 2004 in Japan an average delay has been set and is measured in seconds and which is a 0.2 minute per train, and by European standards it is 100% on time. Today, Japan's HSR is the most reliable in the world. Spanish National Railway Network (RENFE) has a punctuality level of 98% (Watson et al., 2017a). If a train arrives with a delay of over five minutes, all passengers will get a 100% refund of the ticket price.

There have been dramatic changes in accessibility of high-speed trains in Spain, and by 2020, 90% of the population will have an HSR station within a 30miles radius. In the last ten years, the Spanish government has put more financial resources into developing HSR than in highways (News.bbc.co.uk., 2019). The Spanish HSR have significantly increased the level of accessibility to access trains and stations by installing elevators, moving stairways, and offered help for vulnerable passengers when entering the train. In 2009, RENFE proposed a car service system for vulnerable passengers called ATENDO. This programme covered over 240 stations and during the first-year assistance was provided on 235571 occasions (Renfe.com., 2019).

The Talgo 350, class S102 has the nickname ‘The Duck’ which has served since 2005 and has an operating speed of up to 300kph, it is one of the fastest trains in Europe. These trains have 12 coaches and two locomotives with a capacity of 314 and a maximum axle load of 17 tons (Uic.org., 2019b). The new generation of Talgo trains is Talgo Avril. This train is designed for speeds up to 380kph, with a low floor to improve the accessibility for vulnerable passengers.

This train will consume less energy because of its lightweight construction, will produce less noise and vibration, and generate less carbon dioxide emissions. The Talgo Avril train comprises two powered cars one in the front and one at the back and 12 carriages with a capacity of up to 600 passengers. The train can automatically switch between different track gauges (1435 or 1668 or 1520mm) and can be run on diesel or electric or both (Talgo.com., 2019). Also, this train can use AC or DC electrification systems to run the train.

Rail safety in Spain does not have such a good record as in Japan. The latest crash happened on 24 July 2013 with 80 fatalities and 144 were injured from 224 passengers on the train (Shultz, 2017). This happened when the train travelled from Madrid to Ferrol. The accident was caused by the driver going too fast. For the section of line speed was restricted to 80kph, but the train was travelling at 192 kph. This was the deadliest railway crash in Spain over the last 40 years.

The development of railway infrastructure in Spain, as in Germany, is the responsibility of the State. Spain subsidises HSR heavily, and the cost is around $3billion per year (Bodman, 2019). HSR in Spain on many routes is not profitable because of the low occupancy of trains. There are a few reasons for low occupancy: high unemployment, high ticket prices, many towns with HSR stations are small and can only generate a few passengers. Because of the high cost of developing the HSR system, it looks that the development of the HSR systems in Europe and around the world will be in the majority financed by public funding.

A.4 HSR in Germany

The Intercity Express (ICE) trains were designed and built by a Siemens-Led consortium and is operated by the German Federal Railways (DB). ICE has been running since 1988. Germany has 1658km HSR in operation, 185km under construction and 210km in the planning stage. (Uic.org., 2019c). The development of HSR in Germany relieved the increasing demand for air and auto travel. Germany has twice the density of the population of France and taking into consideration that the territory of Germany is smaller than that of France, this can be a good foundation for success of the HSR system.

The HSR now connects all the largest cities of Germany, and it is in the centre of the country's transport system. ICE1 was introduced into service in 1991 and it composes of two power cars, one in the front and one at the back, and twelve carriages between them. It has a maximum axle load of 19,5 tons, 358m long and has a capacity of 703 seats. Germany has 59 sets of ICE1, the train has a 280km/h maximum operational speed, powered by electricity from the overhead catenary 15kV (Uic.org., 2018). ICE1 has three signalling systems, LZB, PZB and ZUB, which is suitable for traffic to Switzerland.

All railway lines in Germany have a standard gauge of 1435mm and electrified at 15kV AC 16.7 Hz. The new lines are designed for speeds up to 300kph. Figure A.6 shows the HSR network in Germany in 2015.

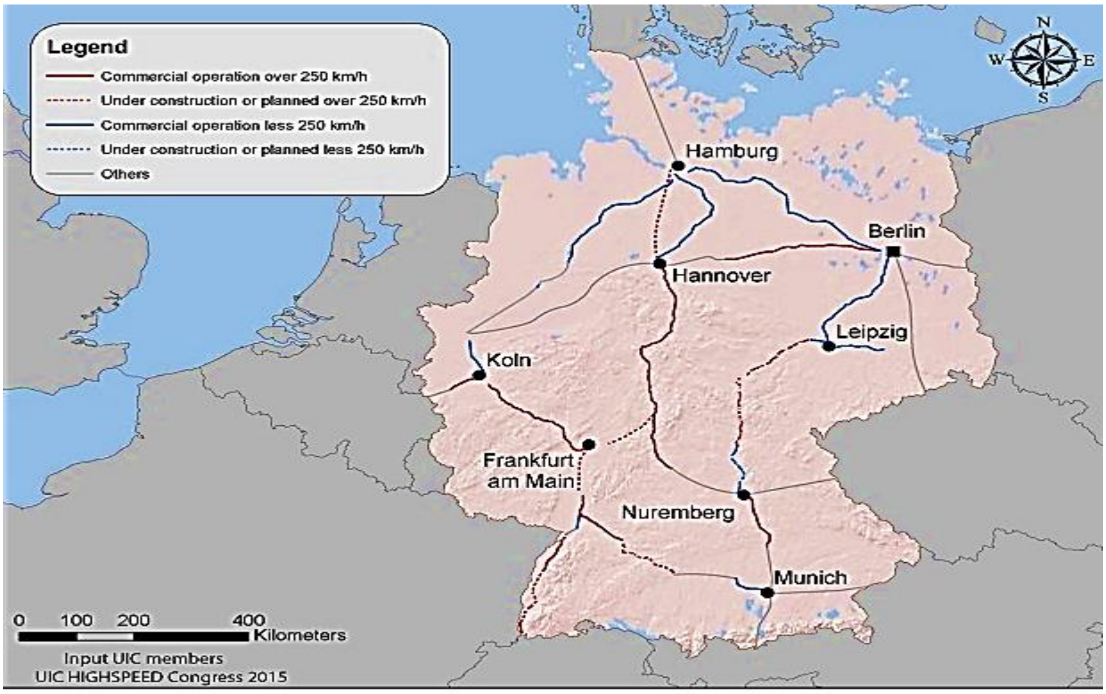

Figure A.6 HSR network in Germany (Source: UIC - International union of railways., 2019d).

From the beginning DB (German Federal Railways) allowed all categories of trains, including high-speed trains and freight trains to use the conventional lines and HSR lines also, but only some trains must run at a lower speed. This decision to allow freight trains to use the HSR was due to the amount of income that freight transportation brought into Germany. This decision differed from Japan and France, where HSR lines are dedicated only for passenger traffic. The mix of traffic brings some disadvantages, for example, if trains with different speeds use the same line, it will decrease the line capacity and can increase the safety problems.

The current ICE trains are limited to 250kph, as other trains with lower speed also use the same track. It is problematic to produce a timetable that satisfies both passenger traffic and freight traffic because of the significant speed differences. Most of the daylight time was allocated to passenger trains, but during the night the line needed to be maintained. This caused some serious delays for freight transport. With increasing the number of real time sensors to monitor the condition of infrastructure and rolling stock and with implementing the proactive maintenance instead of reactive will be decreases in the cost and time that needs of maintenance.

Many railways tracks have been upgraded in Germany, but with the mix of traffic, German HSR lines cannot compare with the French network. To travel fast, there is a need to have not only advanced rolling stock but modern infrastructure too. Travelling time in France will be half of that in Germany for the same length of a journey on railways. For example, travelling time from Paris to Marseille (661km) is 3 hours and 17 minutes (Eurorailways.com., (2019), but a similar distance between Hamburg and Munich (791km) will take 6 hours (Eurail, 2019).

Another reason that affects travelling time on DB is that there are too many stops for high-speed trains in rural areas with not enough demand for passengers travelling on trains. It must be a combination of trains that have many stops and direct trains similar as on Tokyo-Osaka route. Shinkansen has a good mix of direct trains with only a couple stops or none, and trains that serve numerous stations. The biggest environmental impact from HSR is noise pollution. In Germany, noise legislation for railways has been in force since 1974. The maximum noise levels for the new build or upgraded transport infrastructure in Germany are as follows in Table A.1.

Table A.1 German maximum noise level for new built or upgraded transport infrastructures (Source: Europarl.europa.eu., 2019)

Location	**L Day**	**L Night**
Near schools, hospitals	57	47
Residential areas	59	49
Central or mix areas	64	54
Industrial areas	69	59

Germany spends annually €150 million to mitigate noise pollution from railways, and by 2020, they reduced the noise level by 10dB (Uic.org., 2019d). Because of this legislation some parts of newly built high-speed lines have been built in cut-and-cover tunnels to reduce the noise level and visual impact for areas with a high density of population.

The latest ICE3 trains were introduced in 2000 with a maximum operational speed up to 300km/h. The power system of ICE3 has been moved from the two ends to the underside of the cars, which is the same system as used in Japan. The train comprises 8 coaches, 4 of which are powered. As trains do not have a power car, it increases the capability of trains as more seating is available for passengers; it has 429 seats per train (Uic.org., 2019b). Passengers are separated from the driver by a glass screen and this allows the passengers to see the track ahead. The distributed power system has other advantages, and one of them is the low axle load, which is 16 tons per axle, and this will reduce maintenance costs.

ICE3 has one of the best braking systems. Braking equipment on ICE3 comprises 3 systems, and one of them is the regenerative system. Also, ICE3 has a smaller loading gauge than previous ICE1 and ICE2 these changes have been done to allow operation on the European network, for example France did not allow ICE trains on their network before as ICE was too wide and too heavy. French railways have a restriction of 17 tons on one axle for HSR lines. The train comprises six intermediate cars and two ends, and it can be two trains coupled together with double the amount of the seats.

The safety of passengers travelling on the railways is paramount for every railway. Germany had a major accident in June 1998 with a fatality of 101 passengers (Cbsnews.com., 2019). After that, ICE trains were equipped with a warning system. At the present time, only ICE trains and Eurostar have been fitted with a warning system that can detect damages in bogies and wheels early. Also, ICE has been equipped with a train control system (LZB).

This signalling system provides the driver with information for several kilometres ahead. The LZB system improves passenger safety and allows an increase in track capacity. Similar signalling systems for high speed trains have been developed in Japan and France. Apart from the advanced train control systems, passenger safety in Germany was secured by not having level crossings on HSR lines.

With increasing awareness about climate change and the finite of natural resources, it is getting more important to look on what type of energy was supplied for HSR. Most of the energy used by DB is generated from fossil fuels. As shown in Table A.2.

Table A.2 Breakdown by origin of electricity used by the railways in 2005 (Source: Ec.europa.eu., 2019c)

Member State	Solid Fuels	Oil	Gas	Nuclear	Renewable	Total
Belgium	11.8%	1.9%	25.3%	58.1%	2.9%	100%
Germany	54.0%	0.1%	8.3%	26.7%	10.9%	100%
Spain	38.0%	3.8%	18.3%	21.5%	18.4%	100%
France	4.5%	1.8	3.2%	85.8%	4.7%	100%
Italy	33.8%	10.0%	41.5%	0.0%	14.7%	100%
UK	37.0%	1.0%	37.0%	20.0%	5.0%	100%

In recent years, in Germany, HSR systems have lost a considerable number of passengers to long distance coaches. From October 2014, DB started to withdraw some trains as competition between long-distance trains and coaches increased (europe, 2019). It looks that DB needs to review the price policy to remain competitive.

To construct, operate and maintain the HSR system is very expensive and after implementing the HSR systems most governments are left with not enough money to upgrade existing railway systems (France). All HSR lines in Germany need to be subsidised by the government. To be successful, HSR needs to be socially, economically, and environmentally sustainable. With a high population and several important administrative and business centres, Germany has good potential to have a profitable HSR system.

A.5 HSR in Italy

Italy was the second country after Japan that introduced high-speed trains and the first train went into operation in 1977, but the line was only completed in 1992. The HSR system in Italy has the standard gauge 1435mm. Italy has 896km of HSR, 53km under construction, and they have plans to build another 152km at the end of 2025 (Uic.org. (2019c). Italy was the only country in the world that opened the HSR network for competition. From 2012, NTV (Nuovo Transporto Viaggiaton) a private HSR company began to operate. Because of the lack of data in this research, only data related to one company, Trenitalia have been taken into consideration. The Italian HSR network will connect with France through a 57.5km tunnel under the Alps, which they started to build in 2013. This project will be completed by 2020 and put into operation by 2029-2030. It will reduce the travel time between Lyon and Turin to 1 hour 47 minutes from current

3 hours 43 minutes. This will significantly increase the flow of passengers and goods between France and Italy and overall, between the North and South of Europe and will improve the connection between London and Rome (Global Rail News, 2019). However, the project is raising some environmental and financial questions.

One of them is the balance of cost and benefit, with a recent decrease in the number of passengers and freight using this corridor. Another major question is related to health. Almost 57.5kilometres will go through mountains and the geological formation contains large amounts of asbestos and uranium. This is a big concern for protecting the workforce who will work on the project. Another issue is that, after excavating these materials, how and where would they be kept. It estimated the total cost of the project at 22 billion Euros (Tunnelsonline.info., 2019), but from previous infrastructure projects experience it could cost up to three times more.

ETR460 Pendolino, a tilting train that went in service in Italy in 1988. For a country with many mountains, it was conventional to use the tilting technology on conventional lines. Through introducing tilting technology, the train can travel around 30% faster. This active tilting technology soon spread around the world, and now around 70% of all high-speed trains are using it (Zhou & Shen, 2011). Pendolino is electric powered with 3kV DC with a designed maximum operational speed up to 250kph.

The train is formed from nine cars. The maximum axle load of an unloaded train is 13.5ton, a train length of 237m with 480 seats (Uic.org., 2018). Different variations of this train are now used in Germany, Spain, and the USA. The ETR500 high-speed train went to service in 1995. It was the first high-speed train that was designed in Italy and only to be used inside Italy. It has concentrated power, two locomotives one at each end and 12 trailers, and the total length of the train is 354m. They manufactured 59 sets of trains (Uic.org., 2018). There was another version of ETR500 designed and built for the Italian and French railway systems. The train was designed for maximum operational speeds up to 300km/h with improved aerodynamic performances, maximum capacity of the train is 671 passengers. The train can run on 3kV DC and 25kV AC.

The latest high-speed train in Italy, the ETR1000 went into operation in 2015. Trenitalia is investing €1.5bn in these trains and will build 50 sets of them. At that moment, they produced 13 sets of these trains. Trains can travel up to 400kph with a maximum operational speed of 300kph, and it is the fastest train in Europe (Ltd, 2019c). ETR1000 is 202m long with distributed traction along the carriages, four motored coaches, and four trailer coaches.

The train has been designed to be compatible with different signalling systems and different electrification systems within the European HSR network. The train has compatibility with the European Traffic Control System (ETCS). The ETR1000 can carry 457 passengers. The cost of this train is around $40 million (Railway Technology, 2019f).

The Italian transport system favoured roads, but this raised concerns about environmental impacts from transportation. In 2003-2004, only 5.9% of passengers and 16.5% of freight was transported by the railways (Global Railway Review,2019). With expanding the HSR network and upgrading conventional lines, HSR will be more attractive to customers. Figure A.7 shows the HSR network in Italy. HSR lines in Italy run from Turin to Salerno, and Italy has more HSR lines in development: from Milan to Venice, from Milan to Genoa and from Naples to Bari (Figure A.7).

Figure A.7 HSR network in Italy (Source: UIC - International union of railways, 2019d)

On the HSR line from Rome to Florence operated the “Frecciarossa” ETR500 trains with four departures every hour from Rome with a maximum operational speed 300kph. The Italian railway has a standard track gauge 1435mm and electrified by 3kV DC. It will take only 1hour and 30 minutes on HSR to get from Rome to Florence compared to a conventional train that takes 3hour and 20 minutes (Eurail, 2019b).

The Rome-Florence line is mostly straight and with no level crossings, with one line in each direction. It is planned to upgrade this line by changing the electrification system from 3kV DC to the European standard of 25kV AC. The same trains also operate on the Rome to Naples line which is 205 kilometres with two departures every hour and a top speed up to 300 km/h (Uic.org., 2019c). This line has 39 kilometres of tunnels and 39 kilometres of viaducts and bridges. Rome-Florence line was the first to introduce the ERTMS.

ERTMS is the most advanced signalling technology in the world. This system uses wireless technology replacing the signals along the railway track. A computer inside the train cabin controls the speed limit of the train and braking distance. The ERTMS system can automatically reduce the speed of the train if it exceeds the maximum allowed speed on the line.

This system increases the safety of passengers travelling by train as it prevents human error. It reduces operational and maintenance costs, as there is no need to install and maintain signals along the railway tracks, and it increases the capacity of tracks. This system is known around the world as the most advanced and safe signalling system for high-speed trains. As a trial in the UK, this system was introduced in March 2011 on the Cambrian Line in Shrewsbury and Aberystwyth.

The Naples to Salerno line which is 29km long is a new line, it first went into service in 2008 with a maximum operational speed of 250kph. It was built to reduce congestion on the conventional line, trains run on a voltage of 3kV DC. The Florence to Bologne line is 78km long of which 73.8km of that is in tunnels and 1.1km on a viaduct. The line went into operation in 2009 and the maximum operational speed was 300km/h. The building of this line reduced the travelling time from 59 minutes to 37 minutes. This line was estimated to cost €4.8bn, but the eventual cost was €6.9bn. The line is equipped with the ERTMS signalling system. The Bologne to Milan line is 182km long and went into service in 2009 with a maximum operational speed of 300km/h. The line is equipped with the ERTMS signalling system. This line was the last chain to connect Rome and Milan for high-speed trains (Uic.org., 2019c). Table A.3 shows the construction costs of selected HSR lines in Italy.

Table A.3 Capital costs of HSR in Italy (Source: Reason. org., 2019)

HSR Line	**Construction costs ($billions)**	**Miles**	**Cost per Mile ($millions)**
Torino-Milano	11..68	78	130.0
Milano-Bologna	10.73	115	77.0
Bologna-Firenze	8.82	49	163.0
Roma-Napoli	8.48	129	58.0

Majority of the lines were built close to existing corridors to reduce the environmental impact of the projects. The Italian government had lots of investments put into developing the HSR system in Italy. Widening the HSR network increased the rail market share. Table A.4 shows the changes in rail market share on route Roma-Milan, Italy in 2010.

Table A.4 Modal shift on route Roma-Milan (Source: Ertms.net., 2019)

2008	**2010**
Rail market share: 36 %	Rail market share: 55 %
Air transport market share: 50%	Air transport market share: 35%
Road market share: 14%	Road market share: 9%

Most of the lines have advanced signalling equipment (ERTMS). There was some back down in the integrated Italian HSR network in European system, as Italy has some HSR lines using 3kV DC electrification instead of the standard European system of 25kV AC. Building the new HSR lines and upgrading the conventional lines has successfully reduced the number of domestic flights and car journeys in Italy. With the reduction of flights and car travel, it cut the amount of produced GHG emissions by the transport sector. One of the significant features of the Italian HSR network is the wide introduction of ERTMS that it integrated in interconnection with the European railway network. It opened the possibility to drive the same rolling stock with the same team around Europe with no need to change on the border and carry on at speeds up to 300kph. With building the HSR lines in Italy, they delegated conventional railways to freight transport and to serve the regional passengers.

A.6 HSR in the USA

Before the Second World War trains in the USA were the dominant way for transporting goods and people but by the end of the Second World War railways in the USA the same as the rest of world began to decline steadily. The USA has the largest railway network in the world, but it carries more freight than passengers and the amount of freight that is being carried is also in decline (The Geography of Transport Systems, 2019). There are many reasons the USA is behind other countries by implementing the HSR system. One of those reasons is that in the USA the land that the tracks are on is regulated by the individual states, but transportation decisions are regulated through federal policy.

The development of land and infrastructure is not run by one department, and often the local interest opposes national interest. Another reason is that policies in the USA encourage car ownership: by larger subsidies in highway construction, low density of suburban housing and cheap fuel. All of this encourages people to use private cars. In Europe, the price of fuel is much higher, and taxes make it much more expensive to have a car.

Larger amounts of subsidies in public transport in Europe provide a much higher quality of public transport than in the USA. In the USA, the private cars have become essential to life. Individuals can take up to four trips by car for the cost of one trip by public transport (Reason.org., 2019). The public investment in the US in passenger rail, compared to Europe is insignificant. Figure A.8 shows the increasing greenhouse gas emissions from energy use in the USA in the period 1985-2010.

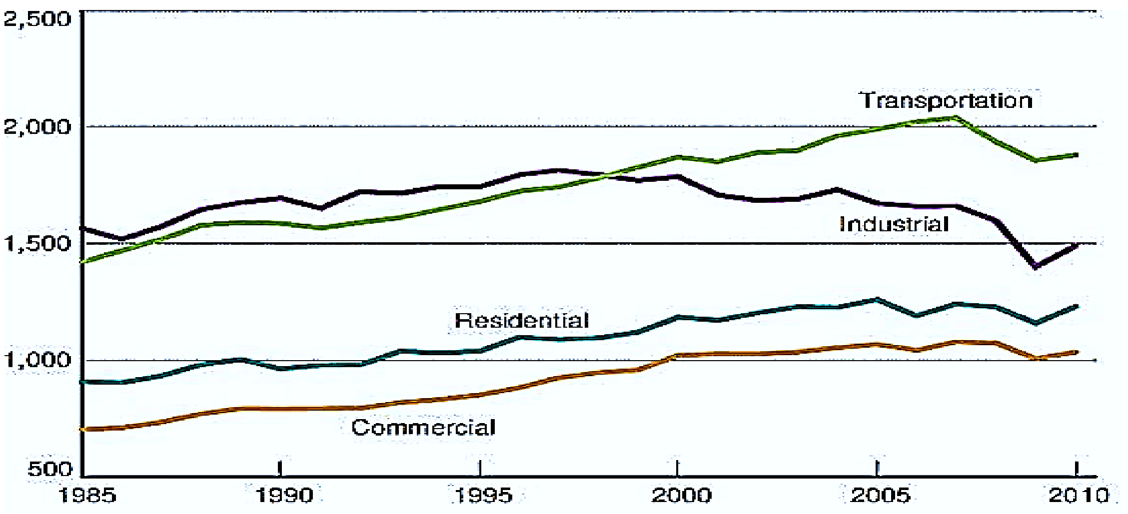

Figure A.8 USA greenhouse gas emissions from energy use: 1985-2010 (Source: Ushsr.com., 2019)

The USA transport system contributes heavily to greenhouse gas emissions. The transport industry consumes on a daily average around 12,500,000 barrels of oil (Statista, 2019). Shifting travel from road to railways can reduce the dependency on crude oil and cut greenhouse gas emissions.

The need to reduce the pollution from road transport will play a key role in the development of HSR. USA has only one HSR the Northeast Corridor from Boston to Washington D.C. 735km long and 192km under construction and is planning to build another 624km by 2025 (Uic.org., 2019c). At the end of 2000, Amtrak introduced a new train, Acela Express, the first high-speed train in the USA and it was very successful.

At the end of 2012, Acela Express brought around 25% of the total Amtrak's service revenue (History.amtrak.com., 2019). Since 2010, Amtrak put approximately three dollars back into the economy for every dollar of federal investment. Amtrak is the private company who owns the line and provided the railway service from 1971 with very limited federal subsidies. The Acela Express runs between Washington D.C. and Boston. This area has a very high density of population.

The Acela Express train went into operation in 2000. This train comprises two powered cars, one at each end and six passenger carriages and in use are 20 sets of trains. The maximum axle load is 23tons, length 203m with a seating capacity of 304 seats, of those 44 are 1st class and 260 are 2nd class (Uic.org., 2018). The Acela Express uses the conventional line that has been upgraded and this limits maximum speed to 240kph, but by using the tilting-train technology it gave the possibility to cut journey time (Dspace.lboro, 2019). Acela II trains will start operating in 2021, and there have been orders to manufacture 28 new trains. Acela II will comprise 2 locomotives and 10 passenger cars with a total seat capacity of 512.

Acela II will be a tilted train with concentrated power and a maximum operational speed of 257kph. New trains will cut travel time by approximately 45 minutes (Uic.org., 2018). Tilting-track technology can be alternative options for building new tracks or straightening existing ones. The tilting technology prevents passengers from having some discomfort from the lateral acceleration, also much cheaper than having to build new tracks. This technology allows the train to have higher speeds in curves, which can reduce the journey time. Figure A.9 shows the tilting bogie technology in Japan, called passive tilt.

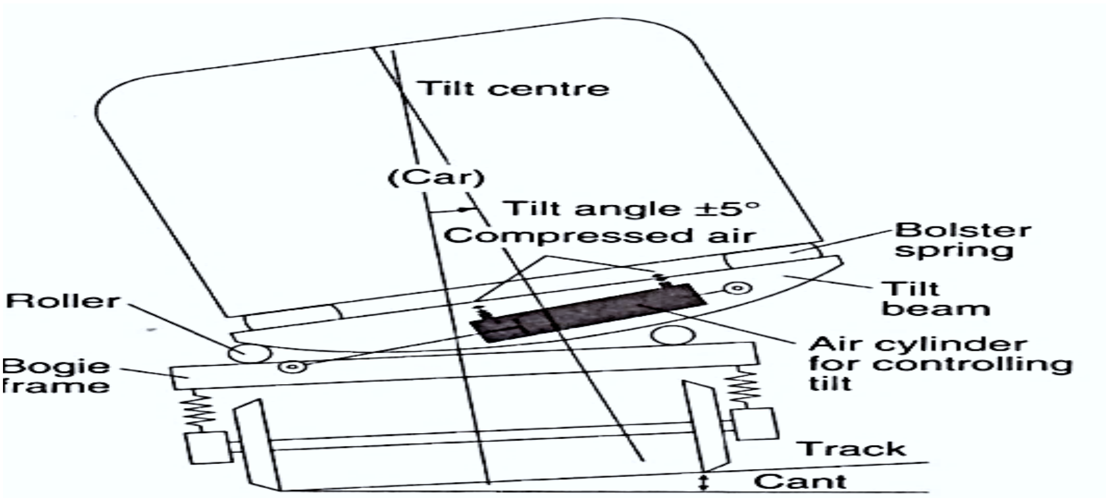

Figure A.9 Roller type tilt system (Source: Japanese Railway Technology Today, 2001)

When the train runs on a curve, the tilting system tilts the body of carriage up to 5^o gradient (Japanese Railway Technology Today, 2001). Also, another tilting system has been developed, the controlled tilt system, called active tilt Figure A.10. Active tilt technology was first implemented in the United Kingdom. The Acela Express has the active tilt technology controlled by a computer.

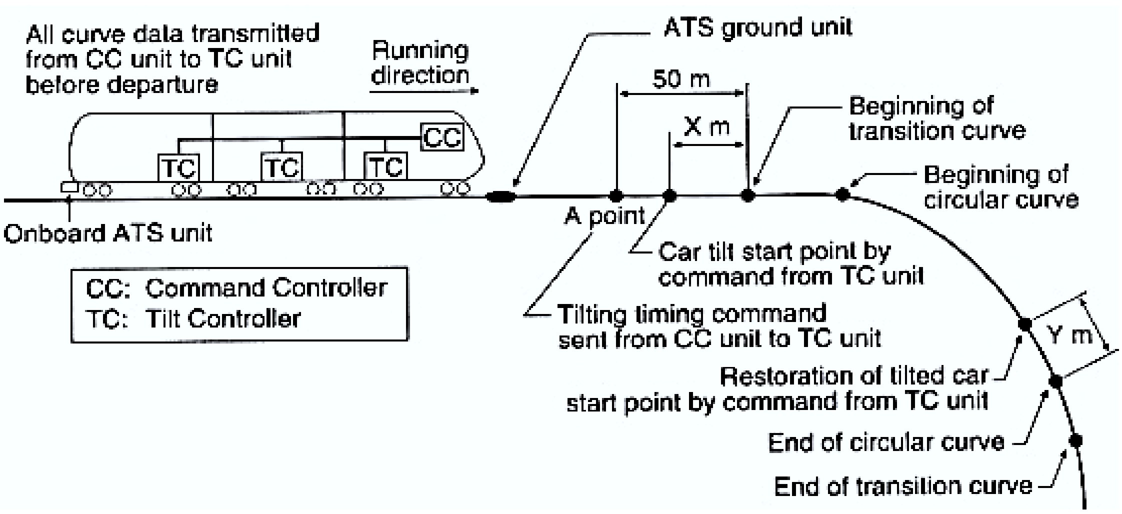

Figure A.10 Principles of controlled tilt systems (Source: Japanese Railway Technology Today, 2001)

The on-board train computer stores all information about the curve radius, alignment, elevation, and the railway line where the train will run. Tilting the carriages start approximately from 30 to 40 metres before the carriages will enter the curve as it was found that it will reduce the passengers feeling the sense of motion sickness.

The track Washington D.C.- Boston stretches through areas with a very high density of population and does not have fences to protect trains from frequently encountered debris. Also, the line between Washington D.C. and Boston has many level crossings. The trains in these circumstances must be built to ensure the safety of drivers and passengers. This increases the weight of high-speed rolling stock.

As the Amtrak needs to have an anti-collision structure, trains are 45% heavier than the similar French TGV trains. Operating speeds for Amtrak trains was limited to 216km/h because of the safety reasons as the same track is shared by freight and passenger trains with much lower speeds. On the northeast corridor from Washington, D.C. to New York high-speed trains carried over 3.5 million rail passengers every year and have 76% percent of the market share between Washington, D.C., and New York (Reason.org., 2019).

A.7 HSR in China

China has the largest HSR system in the world, approximately 60% of the length of the world's HSR network. In 2018, China had 26869km of newly built passenger dedicated HSR lines and 10738km under construction. By 2025 China plan to build another 1525km and by 2030 build an HSR network in the form of eight horizontal and eight vertical HSR lines which will connect the largest cities of China (UIC, CER, 2015). It has been an astonishing expansion of HSR since opening the first line in 2007.

High-Speed lines use the standard gauge of 1435mm (Uic.org., 2019c). The Chinese government has aimed to connect all cities by HSR that have a population of 500,000 or more. At the end of 2020, the total length of new build HSR lines and upgraded will reach 50,000 kilometres (UIC, CER, 2015). It will connect south and north of China and west and east. The next step will be to connect China with Taiwan by an underwater tunnel.

The development of the future HSR system in China involves a huge amount of money, but with the slowing down of the economy in China it looks a very ambitious plan. Although, that the cost to build 1 km of HSR in China is cheaper than in Europe. As estimated by the World Bank, it is between $17-21 million, in Europe it is between $25-39 million (World Bank, 2019). China has some very advanced ideas, and one of them is to connect major cities in the world by HSR, such as London, Moscow, and Paris with Beijing. "One Belt-One Road", is a concept that will connect central Asia with Europe and further (Cheung, 2019). This project involved over 60 countries with more than half the global population.

Passenger traffic on HSR is growing rapidly from 128 million in 2008 to 672 million in 2013 and by 2014 over 2.9 billion passengers used HSR (Documents.worldbank.org., 2019). Although China has the largest population in the world 1.413 billion (Worldpopulationreview.com., 2019b) HSR is still not profitable. One reason can be that ticket prices are too expensive for passengers, and it is around three times higher than the cost to travel on conventional trains. The average population do not earn enough money to travel by HSR, GDP per capita in 2014 was $7000 (Documents.worldbank.org., 2019). Also, many HSR stations in areas where there would be low passenger occupancy. To help to build the HSR profit can be adopted experience of Italian HSR. They are planning to introduce the same model of ticket pricing as on budget airlines to attract more passengers. It looks a reasonably good idea that could be introduced in other countries too. China has a very controversial way how to increase the demand for HSR, they just cut down the number of conventional trains and put passengers in a position when they do not have any other choice apart from HSR.

China has some unproportioned population density with more people living in the east part of China than in the west. Development of new HSR will help to satisfy increasing demand in travel to the east of China. Many people study and work a long way from home, and the Spring Festival season is the one time per year when they go to visit families. Huge demand in this period puts big pressure on the transport system and HSR can relieve this pressure.

The most famous line in China is a line between Beijing and Shanghai. The line's length is 1318km, it cost around €28 billion to build, and it is the third longest HSR in the world (Nkt.com., 2019). It took less than two years to build this line. HSR started operating from 2011. Trains can run at speeds up to 350kph. The line has 23 stops, and in the first year after opening, over 52 million passengers travelled on it (UIC, CER, 2015).

Around ninety trains depart every day between Beijing and Shanghai, there are two types: super-fast with speed up to 300km/h and just fast with speed up to 250kph. The journey time by the fastest train from Beijing to Shanghai is 4 hours 48 minutes. HSR lines can transport freight during night-time (Nkt.com., 2019). It is planned that by 2020 the Chinese HSR network will connect all major cities. Figure A.11 shows the HSR network in China.

Figure A.11 HSR network in China (Source: UIC - International union of railways, 2019d)

China has around 2,500 high-speed train sets. The train CRH380-AL has been designed and manufactured in China, and it first went into service in 2011. It has a maximum operational speed of up to 300kph. CRH380-AL can be formed from 8 to 16 carriages with a capacity up to 1061 passengers. The 16-carriage train has distributed power with 14 motored coaches and 2 trailer coaches, and it is 403 metres long.

This train equipped with 25kV AC 50 Hz electric system, has two braking systems and one of them is the regenerative system which generates electricity when the braking system slows the train down. The train can accelerate up to 380km in seven minutes (Uic.org., 2018). There have been some accusations that China built the CRH380A train using some foreign technologies that were patented but now China are selling trains to other countries without permission from the companies who hold the patents.

Development of a big infrastructure project, such as HSR, plays a very important part in creating new jobs and boosting the economy in areas where the railways go through. With the large expansion of HSR networks in China, some points of safety for travellers have not been as good as they should be. In 2011, a collision between two trains caused 40 people to die, and many more were injured. A signalling system fault caused this collision. Two trains went on the same part of track. Trains have been using the CTCS-2 signalling system (Chinese Train Control System).

This signalling system is analogous to that used for high-speed trains around the world. One feature of this signalling system is that the on-board computer calculates the maximum speed of the train and maximum braking distance. If the driver exceeds the maximum speed allowed on a section, then the train will stop automatically (Fan et al., 2015). Because the signal failed to change from the green to red light, the second train ran on the same section and crashed into the end of the train that was stationary on the same section. Apart from the signalling fault, there was human error too.

This accident had a big effect on the Chinese HSR system, they froze many projects for building new lines. People lost their trust in travelling by high-speed trains. After this accident, all Chinese HSR network was restricted to a maximum operational speed of 300kph and only in 2017 they removed this speed restriction (International Railway Journal, 2019e). On the Beijing-Shanghai line, the maximum operational speed was restored to 350kph. The HSR systems in China have weak competition from road transport, bus services do not expand around the country, also not so many people own cars. The real competition is from airlines and conventional railway lines. Cutting the number of conventional trains, it makes the position of HSR stronger. However, this does not help to reduce the deficit of HSR which makes HSR unsustainable.

A.8 HSR in Turkey

The population of Turkey is almost 82 million and has a land area of 783,562km^2 with a density of population 104.54 per km^2 (Worldpopulationreview.com., 2019). The railways have approximately 1% of a share in passenger transportation (Uysal, 2019a). Turkey has a target for the future to increase the share of railways to 10% in passenger transportation and to 15% in freight transportation (Railway PRO Communication Platform, 2019a). HSR will connect sixteen of the largest cities and the government is planning to connect 55% of the population within an HSR network by 2023 (Railway PRO Communication Platform, 2019b). Turkey's long-term vision for HSR is to carry passengers and freight from hubs around the country and beyond. Turkey wants to integrate into the EU and be a part of the European Single Market and part of the European Transport Network.

Figure A.12 shows that the number of passengers using HSR doubled between the years 2011-2015 and was almost 6 million in 2015 and near one out of every four passengers travelled by HSR in Turkey.

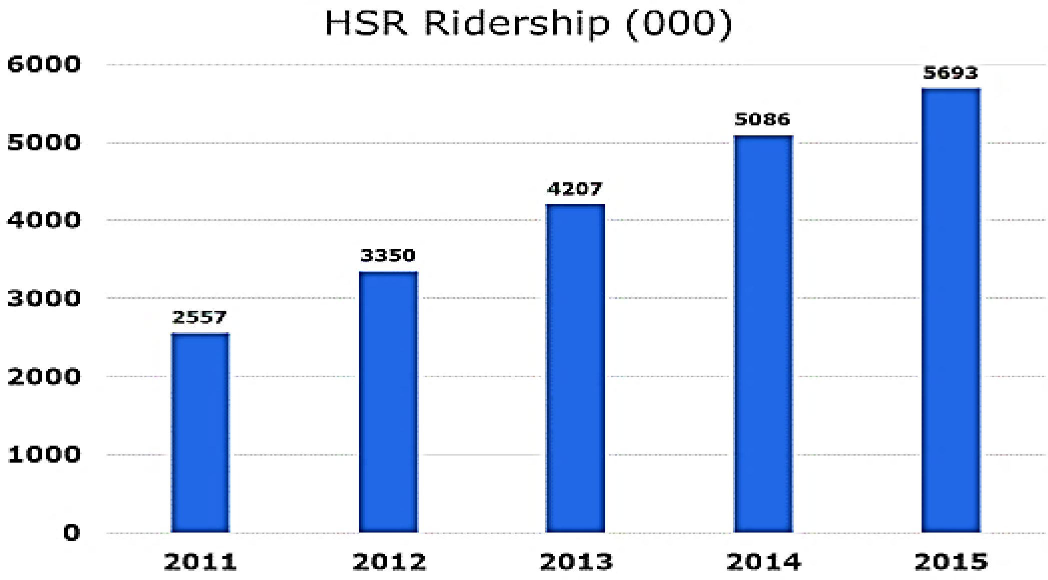

Figure A.12 HSR ridership between 2011-2015 in Turkey (Source: Amended from: Uysal, 2019b)

Turkey has a very favourable location, as a bridge between the Middle East and Europe, and this location gives many advantages. One of them can be The Silk Road Project, which will connect China and Europe by passing through Turkey, which will increase freight and passenger traffic on HSR.

The first HSR which is 232km long was opened in 2009 from Ankara to Eskisehir with a maximum operational speed of 250kph and targeted to transport 9 million passengers annually (UIC, CER, 2015). With the opening of HSR, the travel time between Ankara and Istanbul has been reduced by more than half to just 3 hours from 6 hours and 30 minutes. CAF (Spanish railway vehicle constructor) manufactured the train Class HT65000 for this line. The trains have a maximum operational speed of 250kph, have distributed power, comprising four motor coaches and two trailer coaches and have a capacity of 419 seats (Uic.org., 2018). The HSR lines are equipped with an ETCS Level 1 signalling system.

The number of passengers on HSR Ankara-Eskisehir continuously increased from 0.94 million in 2014 to 3.44 million in 2016 (Uysal, 2019c). In 2016 there were 38 high-speed trains per day but by 2023 it will increase to 300 services per day which will carry 120,000 passengers (International Railway Journal, 2019f). Turkey has 724km of HSR in operation, 1395km under construction and 4574km are planned to be built (Uic.org, 2019c).

The Turkish government has ambitious plans by 2023 to interconnect all major metropolitan and industrial areas by the HSR network, and passenger numbers can increase to 945 million per year. The development of HSR is funded mostly by the government and by credits from foreign banks (Transport-exhibitions.com., 2019). Turkey has the 5th largest HSR network in Europe and the 9th largest in the world. Table A.5 shows the HSR lines under construction in Turkey.

Table A.5 HSR lines under construction in Turkey (Source: Uic.org., 2019c)

Section	**Max. Speed (kph)**	**Distance (km)**
Bursa — Osmaneli	250	105
Kayaş — Yerköy	300	152
Yerköy — Sivas	300	245
Polatlı — Uşak	300	278
Uşak — İzmir	300	192
Konya — Karaman	200	102
Sivas -Erzincan	250	242
Adana—Osmaniye	200	79

The State Railways of the Republic of Turkey (TCDD) ordered the manufacture of 17 new HS railway trains Velaro-D Class HT80000, with distributed power, with 4 motored coaches and 4 trailer coaches, and with a maximum operational speed of 300kph from Siemens (Siemens.com., 2019). Also, Turkey intends to purchase another 106 high-speed trains. However, one of Turkey's targets is to manufacture all HSR stock in house and convert existing RS to be compatible with HSR.

When all HSR lines are completed travel-time will be significantly reduced. Table A.6 shows the changes in travel time on selected routes by introducing HSR services.

Table A.6 Changes in travel time on selected routes with introducing HSR services (data taken from various resources)

Route	Current travel time by train	Travel time by HSR
Ankara-Sivas	10 hours	2 hours
Istanbul-Sivas	17 hours 42 minutes	5 hours
Bursa-Ankara	5 hours 4 minutes	2 hours 15 minutes
Bursa-Istanbul	N/A	2 hours 15 minutes
Ankara-Izmir	14 hours 55 minutes	3 hours 30 minutes

A.9 HSR in Taiwan

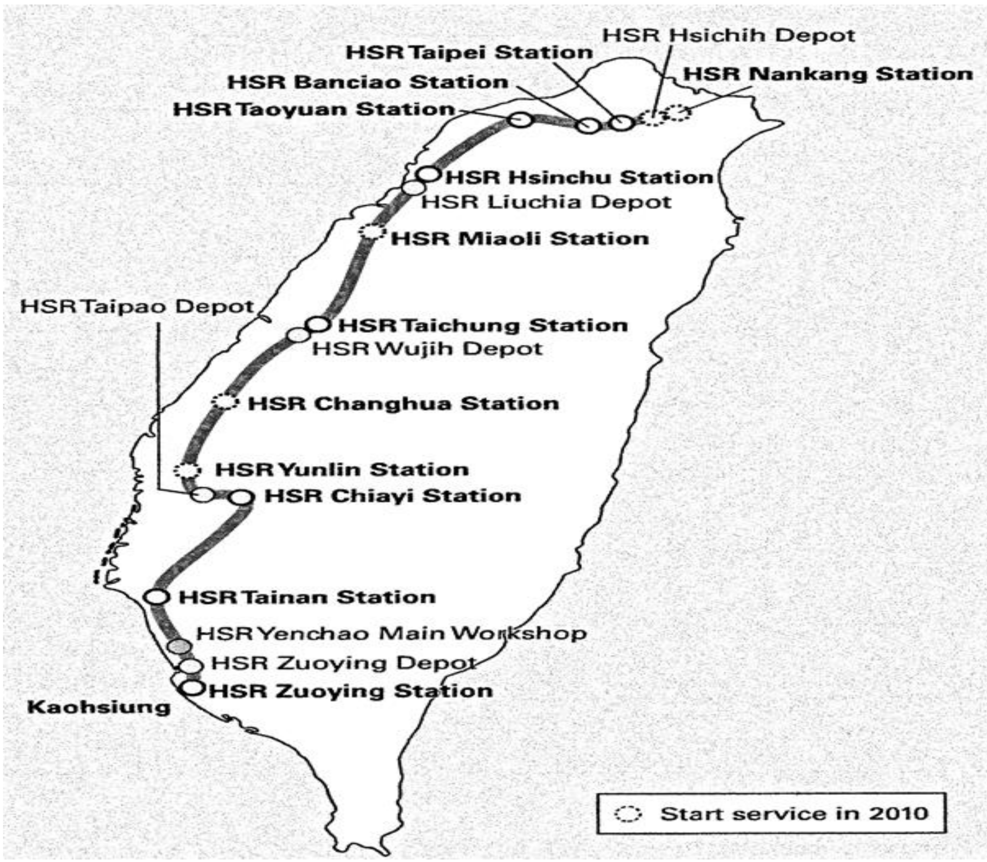

Figure A.13 HSR network in Taiwan (Source: Shima, 2019)

Figure A.13 shows the route of HSR in Taiwan. The HSR in Taiwan comprises one double track line 354km long. The line runs along Taiwan's western corridor from the capital of Taiwan (Taipei) to the main industrial city of Kaohsiung on the south of the island. These are the two largest cities in Taiwan. The first 345km of HSR in Taiwan went into operation on 5th January 2007 with a maximum operational speed of 300kph from Taipei to Kohsiung. In 2016, an additional 9km was built from Taipei to Nangang. In September 2018, the government announced that by 2029 they will build a new HSR line from Kaohsiung to Pingtung 17.5km long. The estimated cost of a new line is $1.78 billion (News, 2019).

The line has a standard gauge of 1435mm and built on the slab track. To avoid crossing roads on the same level, 90.7% of the line was built in tunnels and on viaducts. The total cost of HSR was estimated to be $15 billion (Bradsher, 2019). Figure A.14 shows the ratio of structure type by length.

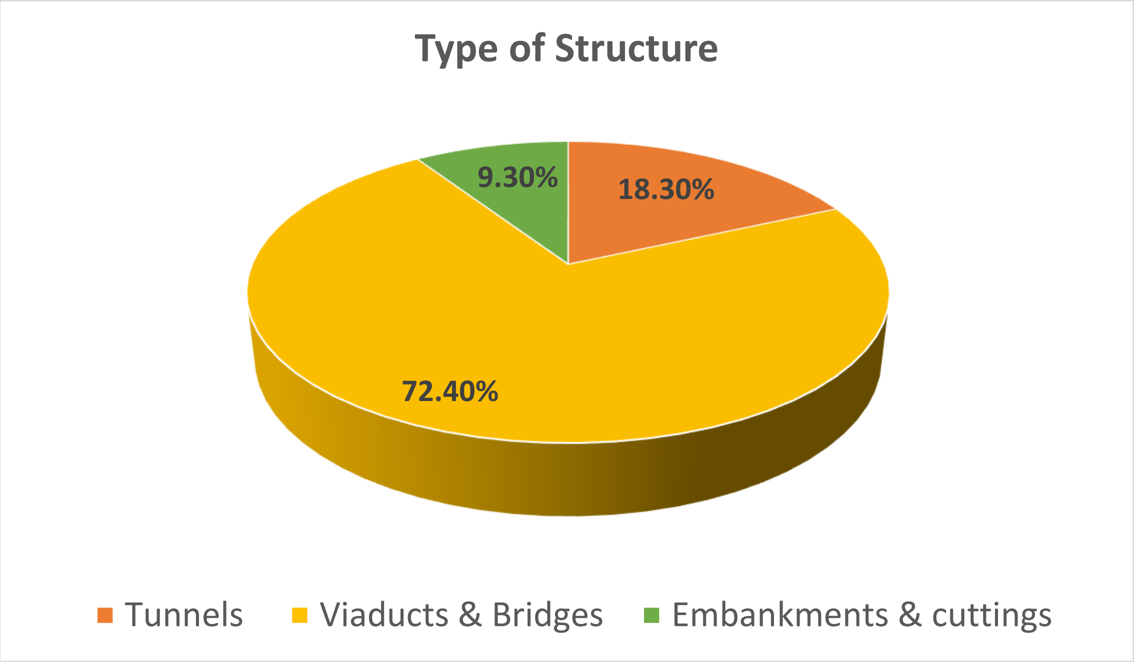

Figure A.14 Ratio of structure type by length created by Author (Data adapted from Shima, 2019)

From 2010 to 2017, traffic increased from 7.5 to 11.1 billion passenger-km per year (Uic.org, 2019b). This line links towns and cities with 94% of the total population in Taiwan. The development of this line reduced the number of car journeys and the number of flights. As a result, it reduced the dependency of Taiwan on the export of petroleum and reduced CO_2 emissions from the transport sector. It was estimated that passengers on the HSR used half the energy and produced a quarter of CO_2 emissions compared with bus travel.

In 2013, ridership in a single day reached 200 thousand, and in 2018 it increased to 285 thousand. The development of HSR decreased the number of flights and car trips. The number of domestic air passengers in 1997 was 18 million, but with the HSR coming into operation, it dropped to 6 million in 2007. In 1997-1998 Mandarin Airlines had over 100 flights daily between Kaohsiung and Taipei but after HSR went in operation, the number of flights dropped to three per week (Focustaiwan.tw, 2019a). In 2017, the number of passengers using HSR increased to 60.57 million with 198 daily services. The total number of trains reached 51751 with a 65.16% occupancy rate. The initial ticket for a 345km journey cost $44. It is two-thirds of the airline ticket price (Bradsher, 2019). THSRC has an excellent punctuality rate of 99.72% (Thsrc.com.tw, 2019).

The HSR in Taiwan is based on the technology of the Shinkansen. This is a new line, and as often to reduce the cost of the project, the stations are located outside of cities. Passengers can reach a station by a free shuttle bus from the centres of towns. In 2017, it provided 393819 free shuttle journeys (Thsrc.com.tw, 2019). Also, each station has parking space, car rental service, taxi, metro, and bus services.

According to UIC HS Rolling Stock tables (Uic.org, 2018b) Taiwan has in operation 34, T700 trains. The design of trains is based on the Series 700 Shinkansen and modified for THSR. Trains went into operation in 2007. The number of trains will increase to 54 by 2033. Each train comprises nine motor coaches and three trailer coaches. The maximum operational speed is 300kph. Each EMU has a length of 304 metres and has 989 seats, one coach first class with 66 seats and eleven coaches second class with 923 seats. The train is powered by an overhead electric line with a voltage of 25kV 50Hz, equipped with a signalling system that allows operation on both tracks in both directions. The HSR line is equipped with an Automatic Train Control (ATC) system. However, in 2017 a major incident happened when a train ran on the wrong track in the wrong direction, fortunately the train was not carrying passengers (Focustaiwan.tw, 2019b). The trains are equipped with an earthquake early warning system. This system allows the train to stop or slow down 10 seconds before an earthquake hit.

To cover 354km without stops, it takes only 96 minutes and in 2007 there was 61 trains every 24 hours in each direction, from 7am to 9:06pm. By 2018 they expanded it to 90 trains from Southbound, with the first departure at 6:15am and last departure at 10:50pm and 95 trains from Northbound with the first departure at 5:50am and last departure at 10:55pm. The trains have different stopping patterns from non-stop to local trains, which stops at each station and with a maximum of total 210 runs per day. To allow this number of runs, the increased noise pollution, CO_2 emissions and threat of land subsidence along the route was assessed and evaluated. In 2015, the number of stations reached 11, and the running time of trains stopped at each station reduced to 138 minutes. In 2017, the number of stations increased to 12 (Taipeitimes.com, 2019). Table A.7 shows the increased ridership on HSR in Taiwan from 2013 to 2017.

Table A.7 Operating Statistics 2013-2017 Created by Author (Data adapted from Thsrc.com.tw, 2019)

Year	Total Ridership (in millions)	Train services per year	Occupancy (Passenger-km/seat-km)	Punctuality rate (% of trains arriving within five minutes of scheduled time)	Passenger-km (in millions)
2013	47.49	48859	57.59%	99.38%	9.118
2014	48.02	50467	57.12%	99.61%	9.235
2015	50.56	50532	59.65%	99.66%	9.655
2016	56.59	51106	63.52%	99.43%	10.488
2017	60.57	51751	65.16%	99.72%	11.103

In 2015, Taiwan High-Speed Rail Corp (THSRC) a private company that built and operated HSR in Taiwan, was close to bankruptcy. This was caused by a wrong projection of ridership and high depreciation costs of trains. Also, the high price of tickets deterred people from using the HSR. The government stepped forward and saved the THSRC from bankruptcy (U.S., 2019).

A.10 HSR in South Korea

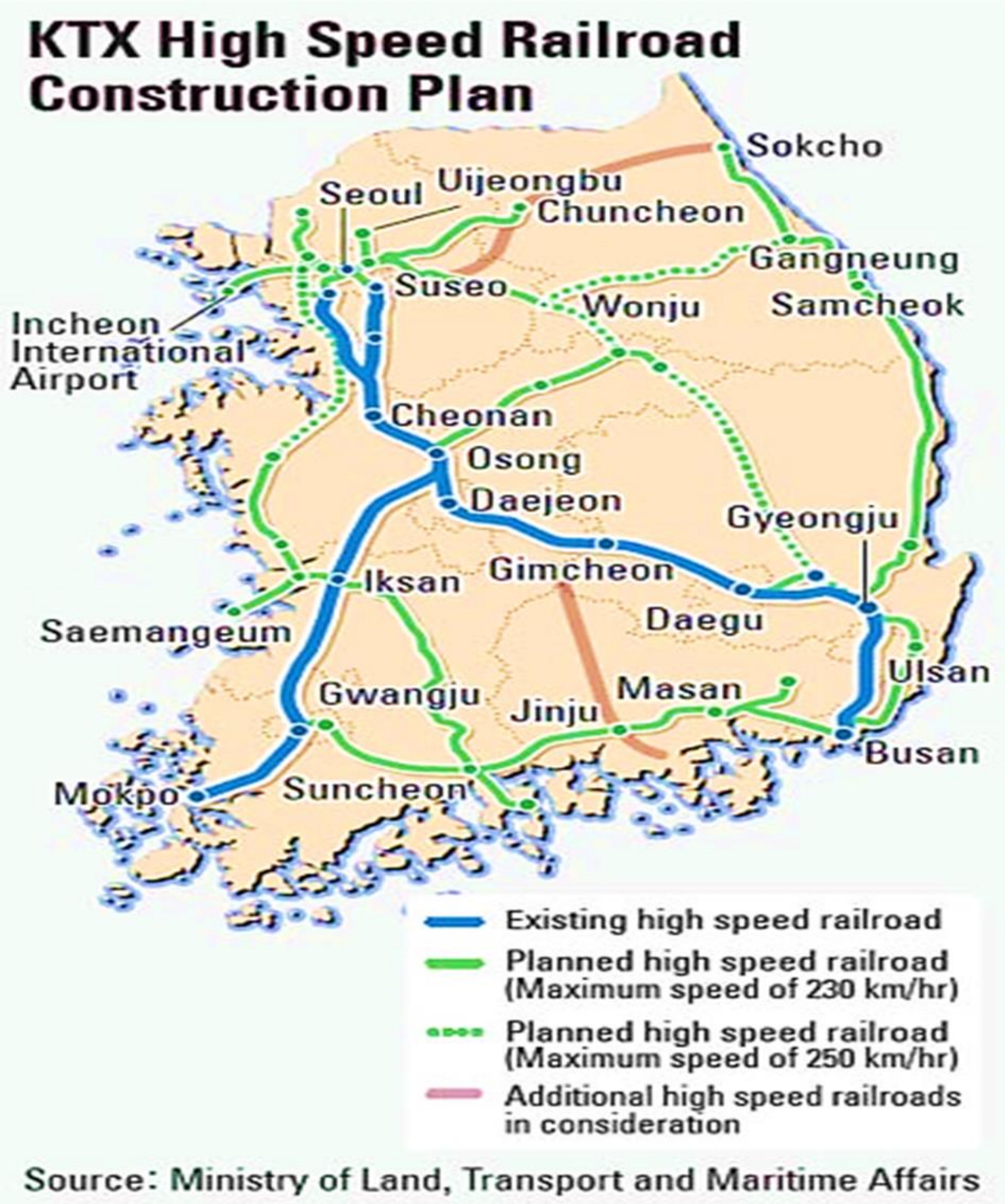

Figure A.15 HSR construction plan in South Korea (Korea JoongAng Daily, 2019a)

Figure A.15 shows the HSR network in South Korea. The first HSR line from Seoul to Dongdaegu went into operation on 1st April 2004 (Uic.org, 2018b). The HSR network comprises two corridors, one from Seoul to Busan, an area where over 70% of the population lives and another one from Seoul to Gwangju. The lines have a standard gauge of 1435mm and built on ballasted track with concrete sleepers. The estimated cost of 411km HSR from Seoul to Busan was $US17 billion. It was an expensive project, as 190km is in tunnels and 120km on bridges and viaducts. The HSR network will be expanded for commuters to travel to most parts of the country in 1hour 30 minutes. Figure A.16 shows the ratio of structure type by length of HSR in the corridor Seoul-Busan.

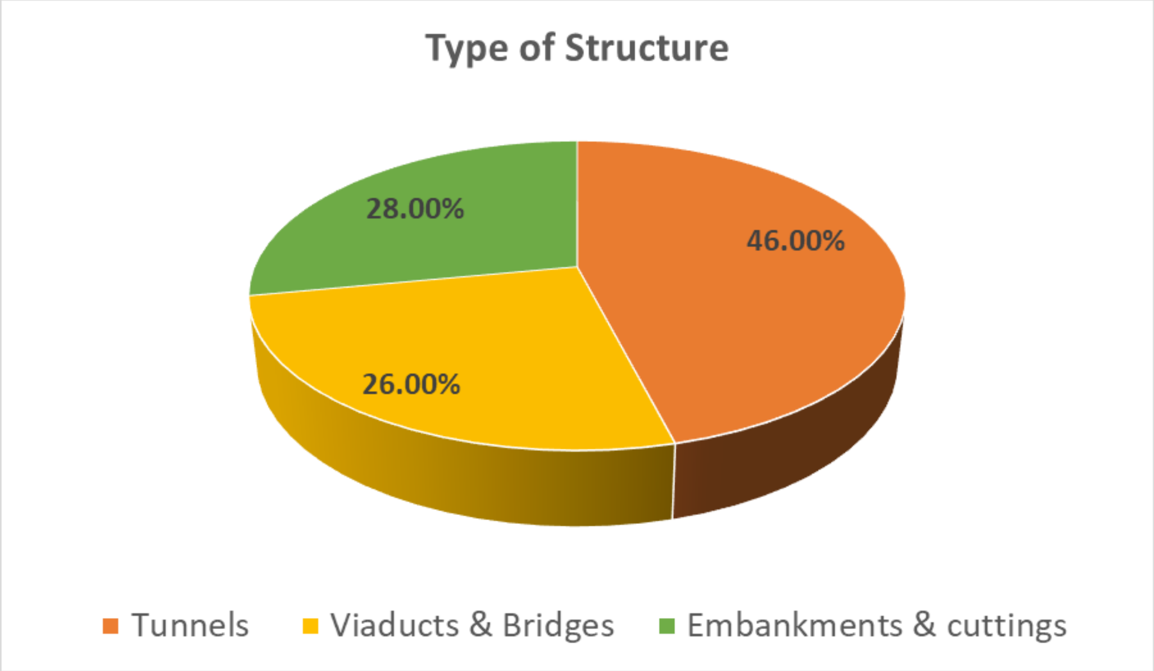

Figure A.16 Ratio of structure type by length of HSR in corridor Seoul-Busan created by Author data taken from (Systraasia, 2019)

It was a huge joint South Korea-France project that involved sending 1000 South Korean engineers to France for training and to adopt French experience in developing and operating the HSR system.

The Seoul-Busan corridor represented 65% of passengers and 70% of freight flows. Because of this, the development of HSR in South Korea improved environmental sustainability by reducing around 33000 cars and 8000 buses per day, reduced congestion on the Gyeongbu Expressway, reduced travel time. Also, this supported demographics and economic decentralization and improved the quality of travel. With the opening in 2004 HSR the travel time on the Seoul-Busan route was reduced from 4 hours and 10 minutes to 2 hours and 40 minutes and after developing a new line between Daegu and Busan times was cut to 1 hour 46 minutes (Railway Gazette, 2019). The train tickets cost approximately 70% of domestic air tickets. After three years of exploitation, Korea Train Express (KTX) in the corridor Seoul-Busan captured over 60% share of all travellers. The number of air travellers dropped from 3.8 million in 2004 to 2.4 million in 2008 (Korea JoongAng Daily, 2019b). Table A.8 shows the HSR lines in Korea.

Table A.8 High-Speed Lines in South Korea on 1st October 2019 Created by Author Data adapted from (Uic.org, 2019c)

Section	Status	Date	Length (km)	Max. Operational speed (km/h)
Seoul-Dongdaegy	completed	2004	288	305
Dongdaegy-Busan	completed	2010	130	305
Osong-Gwangju	completed	2015	184	305
Suseo-Pyoengtaek	completed	2016	61	305
Seoul-Gangneung	completed	2017	230	250
Gwangju-Mokpo	planned	2025	49	305

On the 1st October 2019 Korea has 893km of HSR in operation and they plan 49km to be built, 230km of the HSR has a maximum operational speed of 250km/h and 643km has a maximum operational speed of 305kph.

In the first 10 years from 2004 to 2014, KTX carried around 414 million passengers with an average of 150,000 per day (English. chosen, 2019). Figure A.17 shows the changes in HSR traffic in Korea between 2010-2017.

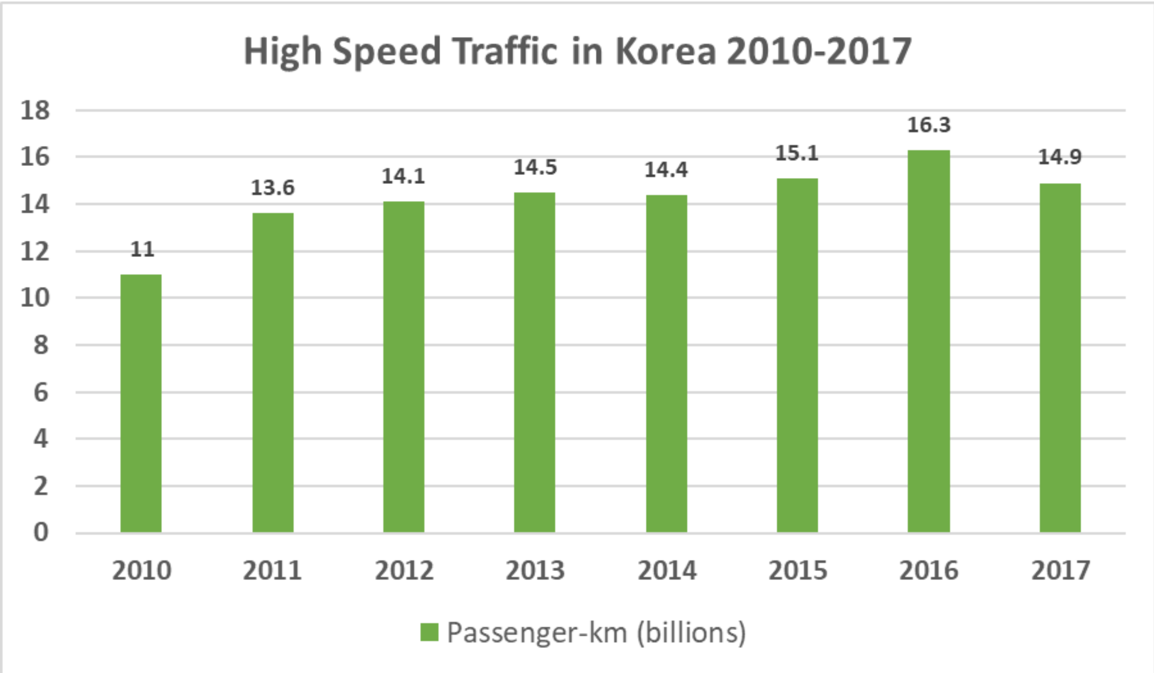

Figure A.17 HSR traffic in Korea (Korail) in 2010-2017 created by Author, data taken from (Uic.org, 2019)

According to UIC HS Rolling Stock tables (Uic.org, 2018b) Korea has in operation 117 KTX (Korea Train Express) trains, with a maximum operational speed of 300kph. The train design was based on the French TGV Reseau.

The first 46 trains went into operation in 2004, 12 of them were supplied by Alstom and 34 manufactured in Korea by HyndaiRotem. Korea was the fourth country in the world after Japan, France, and Germany, which uses its own technology to build trains with a maximum speed of 330km. The first 46 trains have a set formula of 2 locomotives, 2 motorized trailers, and 16 trailer coaches. The trains are 388m long with a maximum number of seats of 935 and with maximum traction power of 13200kW. The latest 71 trains manufactured by HyndaiRotem comprise 2 locomotives and 8 trailer coaches. They are 201m long with 363 seats, 30 seats in first class and 333 seats in second class and a maximum traction power of 8800kW.

These trains a lighter as the car body is made from Aluminium Alloy and the powered car body is made from mild Steel, compared to the first 46 trains which the bodies were made from Steel. The weight of 10 cars is 434 tons. The train is powered by an overhead electric line with a voltage of 25kV 60 Hz, equipped with an Automatic Train Control (ATC) system which is continuously checking the speed of train (Uic.org, 2019b). The HS trains which were developed in Korea caused many safety concerns as they had many technical problems. In 2011, one of the HS trains was stopped for an hour inside a tunnel. In 2018, a KTX bullet train derailed, and 14 passengers were injured (koreatimes, 2019). The Korean’s Government has ambitious plans to extend HSR from Mokpo to the largest island in Korea, Jeju. To implement this plan, Korea must build a 73km underwater tunnel, the largest in the world. The project has an estimated cost of US$ 10Billion.

In the later years, there can be observed an increase in competition from road transport as the Government investments in railways is insufficient. From 1971 to 2004, the length of railway lines in Korea decreased, which increased the number of cars on the road. Also, increased safety concerns about using KTX. All of this negatively influenced HSR ridership, which dropped from 16.3 million in 2016 to 14.9 million in 2017 (Figure A.17).

Appendix B

Detailed data concerning the selected key HSR systems

The Tables below summarizes the data set for inputs and outputs of ten HSRs for the period 2010-2017.

Table B1. Surface area, Population, Density of Population, GDP per capita in 2017 ($) (Source: Uic-stats.uic.org, 2019; Wdi.worldbank.org, 2019; countryeconomy.com, 2019)

Country	**Code**	**Surface Area thousand sq km**	**Population M**	**Density of Population in hab/sq km**	**GDP per capita in 2017 $**
France	FR	549	66.48	121	42.567
Japan	JP	378	126.82	336	48.556
China	CH	9563	1370.84	143	14.936
USA	US	9832	321.19	33	60.200
Turkey	TR	784	76.82	98	27.550
Spain	ES	506	46.46	92	32.405
Italy	IT	301	60.77	202	34.877
Germany	DE	357	80.93	227	46.747
Korea	KR	100.3	51.5	212	26.152
Taiwan	TW	36.2	23.7	649	24.292
The Netherlands	NL	41.5	17.0	410	53.597

Table B2. GDP per capita in the selected countries 2010-2017 (in USA$ 2010) (Source: Data.worldbank.org, 2019; countryeconomy.com, 2019)

Country	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Korea	22086	22724	23123	23685	24323	24870	25484	26152
Spain	30736	30321	29414	29008	29496	30532	31505	32405
Germany	41785	44125	44259	44354	45022	45412	45923	46747
Turkey	10672	11683	12052	12866	13312	13898	14117	14936
Taiwan	19262	20912	21270	21888	22639	22374	22541	24292
The Netherlands	50338	50937	50212	49969	50497	51410	52267	53597
France	40638	41283	41158	41183	41374	41642	41968	42567
China	4560	4971	5336	5721	6108	6496	6894	7329
Italy	35849	35994	34885	33887	33615	33968	34313	34877
Japan	44507	44538	45276	46249	46484	47163	47660	48556

Table B3. Average distance and time travel per passenger in the selected countries in 2017 (Source: calculated by Author)

Country	**Operator**	**Average distance travelling per passenger in 2017 in km**	**Average operational train speed in kph**	**Average passenger time in vehicle in h**
Korea	Korail	249	154	1.61
Spain	Renfe	386	202	1.91
Germany	DB AG	328	168	1.95
Turkey	TCDD	317	149	2.12
Taiwan	THSRC	183	152	1.20
The Nederland	Intercity	100	130	0.76
France	SNCF	464	243	1.90
China	CR	380	282	1.35
Italy	FS	322	191	1.69
Japan	JR	233	203	1.14

Table B4. Origin—Destination, travel time and distance for the selected HSRs in 2017 (Source: various sources)

Country	**Operator**	**Origin-Destination**	**Travel time in hours**	**Distance in km**
Korea	Korail	Seoul-Busan	2.7	417.00
Spain	Renfe	Madrid-Seville	2.33	472.00
Germany	DB AG	Koln-Frankfurt	1.7	286.6
Turkey	TCDD	Ankara-Eskisehir	1.5	224.02
Taiwan	THSRC	Taipei-Kaohsiung	2.25	342.30
The Nederland	Intercity	Amsterdam-Antwerpian	1.25	163.02
France	SNCF	Paris-Marseille	3.08	750.75
China	CR	Beijing-Shanghai	4.67	1320.62
Italy	FS	Milan-Naples	4.08	783.10
Japan	JR	Tokyo-Osaka	2.55	517.24

Table B5. Total number of HS Train sets, Total number of seats, Average Traction Power of Train sets of the selected electrified HSR systems in 2017 (Source: Uic.org., 2018a).

Country	Operator	Train sets	Seats	Average Power (kW)
France	SNCF	410	192813	8770
Japan	JR	398	376461	11500
China	CR	2411	1596810	8960
USA	Amtrak	20	10240	2000
Turkey	TCDD	13	5488	5050
Spain	Renfe	229	60063	5160
Italy	FS	137	69272	7410
Germany	DB AG	257	118698	6700
Korea	Korail	109	67524	10800
Taiwan	THSRC	34	33626	9600
Netherlands	Intercity	26	9802	8800

According to UIC “World HSR Rolling Stock” Germany has 6 train sets powered by diesel. In this research, they are not considered in this research, as it is investigated only the electrified HSRS.

Table B6. Revenue-earning High-Speed Traffic-Total number of passengers in the selected countries (thousand passengers) (Source: Uic-stats.uic.org, 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	41349	50309	52362	54744	49847	56951	64617	59669
Spain	28056	28899	28393	32123	34100	36261	38829	40259
Germany	78506	76100	76600	78770	77951	79451	83422	86732
Turkey	1890	2557	3350	4207	5086	5693	5898	7160
Taiwan	36939	41629	44526	47490	48020	50560	56590	60570
The Netherlands	2796	3020	3166	3475	2284	2423	3507	4098
France	112557	110384	110825	109796	108978	108849	108849	108720
China	285520	285520	372050	537920	703790	961190	1221282	1517800
Italy	33993	37941	39665	39613	39961	40340	41445	41276
Japan	294153	307284	323535	335590	341876	360930	365014	377743

Table B7. High Speed traffic in the selected countries, passenger-km (millions) (Source: Uic.org., 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	10981	13561	14083	14451	14433	15102	16324	14869
Spain	11715	11231	11177	12744	12788	14129	15059	15540
Germany	23903	23305	24753	25178	24316	25280	27213	28502
Turkey	476	665	914	1186	1555	1847	1871	2218
Taiwan	7491	8148	8643	9118	9235	9655	10488	11103
The Netherlands	285	305	324	363	242	996	365	413
France	51890	51386	51086	50786	50659	49980	54130	58280
China	46300	105842	144610	214110	282495	386306	464104	577635
Italy	11338	12283	12794	12489	12773	12997	12997	12997
Japan	77732	82078	89483	89483	90613	97699	99221	101325

Table B8. Average distance travelled per passenger on HSRs, km (Source: Uic-stats.uic.org, 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	n/a	n/a	n/a	n/a	n/a	n/a	253	249
Spain	418	389	393	396	n/a	n/a	387	386
Germany	304	306	323	319	311	318	326	328
Turkey	252	260	272	281	n/a	n/a	317	n/a
Taiwan	n/a	n/a	n/a	n/a	n/a	n/a	185	183
The Netherlands	n/a	n/a	n/a	n/a	n/a	n/a	104	100
France	461	467	460	463	464	n/a	n/a	n/a
China	n/a	n/a	386	n/a	401	401	380	380
Italy	341	324	322	n/a	n/a	n/a	n/a	n/a
Japan	257	262	262	259	252	n/a	233	n/a

Table B9. Average time travelled per passenger in the selected countries in period 2010-2017 in hours (Source: calculated by Author)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.61
Spain	2.07	1.93	1.95	1.96	1.94	1.94	1.92	1.91
Germany	1.54	1.82	1.92	1.99	1.85	1.89	1.94	1.95
Turkey	1.69	1.74	1.82	1.88	2.00	2.00	2.12	2.12
Taiwan	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.20
The Netherlands	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.76
France	1.89	1.92	1.89	1.90	1.90	1.90	1.90	1.90
China	1.36	1.36	1.36	1.39	1.42	1.42	1.34	1.34
Italy	1.78	1.69	1.68	1.68	1.68	1.68	1.68	1.68
Japan	1.26	1.29	1.29	1.27	1.24	1.19	1.14	1.14

Table B10. High-Speed Lines in the selected countries with line speed 250 kph and over (there are some exceptions) in km (Source: Uic-stats.uic.org, 2019; Uic.org.,2019c)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	369	369	369	369	369	596	657	887
Spain	1684	1759	1809	1919	1908	1908	2503	2852
Germany	864	864	864	881	881	880	994	1658
Turkey	232	444	444	444	632	724	724	724
Taiwan	345	345	355	345	345	345	350	354
The Netherlands	n/a	n/a	n/a	n/a	n/a	n/a	n/a	120
France	1848	1857	1857	1857	1857	2043	2166	2814
China	4675	6095	8442	10437	n/a	18752	20305	26869
Italy	685	652	652	675	856	856	909	896
Japan	2620	2620	2620	2620	2743	n/a	n/a	3041
USA	n/a	n/a	n/a	n/a	n/a	n/a	n/a	735

Table B11. Land taking by the selected HSRs in ha (Source: calculated by Author)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	1845	1845	1845	1845	1845	2980	3285	4435
Spain	8420	8795	9045	9595	9540	9540	12515	14260
Germany	4320	4320	4320	4405	4405	4400	4970	8290
Turkey	1160	2220	2220	2220	3160	3620	3620	3620
Taiwan	1725	1725	1775	1725	1725	1725	1750	1770
The Netherlands	600	600	600	600	600	600	600	600
France	9240	9285	9285	9285	9285	10215	10830	14070
China	23375	30475	42210	52185	72970	93760	101525	134345
Italy	3425	3260	3260	3375	4280	4280	4545	4480
Japan	13100	13100	13100	13100	13715	14460	14460	15205
USA	3675	3675	3675	3675	3675	3675	3675	3675

Table B12. Mean annual staff strength-all sectors (full-time equivalent) (Source: Uic-stats.uic.org, 2019)

Code	Op-or	2010	2011	2012	2013	2014	2015	2016	2017
KR	Korail	29958	29267	28967	27930	27461	26498	26394	26352
ES	Renfe	13833	13955	13866	14835	14319	142116	13960	14233
DE	DB AG	251810	282300	286237	293765	296094	297170	302204	308800
TR	TCDD	28321	25836	27680	25770	25424	25418	24127	23330
TW	THSRC	3168	3353	3222	n/a	n/a	n/a	n/a	n/a
NL	NS	9855	9683	7959	8230	8472	8767	10845	31404
FR	SNCF	152387	150454	150653	150070	148932	139448	n/a	136642
CH	CR	20674 $x10^2$	20511 $x10^2$	20326 $x10^2$	20963 $x10^2$	20227 $x10^2$	20023 $x10^2$	20040x 10^2	18415 $x10^2$
IT	FS	82566	76417	72341	71031	69487	69276	69056	72441
JP	JR	121532	121217	121749	121966	121107	119893	121193	114870
US	Amtrak	20047	n/a	n/a	20500	20743	20388	20377	20249

Table B13. Electric power consumption by railways in the selected countries (gWh) (Source: Uic-stats.uic.org, 2019; studylib.es., 2019; Renfe.com., 2019b)

Code	Operator	2010	2011	2012	2013	2014	2015	2016	2017
KR	Korail	1965	2183	2028	2103	2070	2178	2735	n/a
ES	Renfe	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2621
DE	DB AG	9466	9277	9091	8672	8374	8302	8162	7969
TR	TCDD	226	214	197	173	192	196	217	n/a
TW	THSRC	458	446	443	n/a	n/a	n/a	n/a	n/a
NL	NS	1287	1194	1186	1164	1145	1187	1230	1067
FR	SNCF	7782	7787	7700	7687	7469	6392	n/a	6300
CH	CR	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
IT	FS	4350	3966	3720	3910	n/a	n/a	4220	4222
JP	JR	6569	6368	6502	6521	6513	6519	6510	6525
US	Amtrak	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table B14. Density of population in the selected countries (people per sq km of land area) (Source: Data.worldbank.org.,2019b; countryeconomy.com., 2019)

Country	2010	2011	2012	2013	2014	2015	2016	2017
Korea	509	513	515	517	520	523	525	527
Spain	93	93	93	93	92	92	93	93
Germany	234	230	230	231	232	234	235	236
Turkey	93	95	96	98	100	101	103	104
Taiwan	644	645	648	650	651	653	654	655
The Netherlands	492	495	496	498	500	502	505	508
France	118	119	119	120	121	121	122	122
China	142	143	143	144	145	146	146	147
Italy	201	206	202	204	206	206	206	205
Japan	351	350	350	349	349	348	348	347
USA	33	34	34	34	34	35	35	35

Appendix C

Summarised results of the CRS output-oriented MI DEA model

Appendix C Summary results of the CRS Output-Oriented MI DEA model

Table B1 shows the results for Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C1 shows the changes in efficiency for the period 2010-2011.

Table C1. Results of CRS MI DEA simulation for the period 2010-2011

	Period:	2010 to 2011	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	2.22	1	2.22	100	100	
ES	0.22	0.74	0.29	23.38	17.37	
DE	0.96	0.79	1.22	92.97	73.4	
TR	0.11	0.58	0.19	7.26	4.22	
TW	1.71	0.93	1.84	95.37	88.5	
NL	0.19	0.89	0.22	20.75	18.46	
FR	0.99	0.8	1.23	94.36	75.3	
CH	1.24	0.87	1.43	54.4	47.25	
IT	1.14	0.92	1.23	55.62	51.26	
JP	1.06	0.86	1.23	100	86.02	

Table C2 shows the results for the Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C2 shows the changes in efficiency for the period 2011-2012.

Table C2. Results of CRS MI DEA simulation for the period 2011-2012

	Period:	2011 to 2012	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	2.03	1	2.03	100	100	
ES	0.2	0.93	0.21	17.37	16.19	
DE	1.04	1.02	1.01	73.4	75.07	
TR	0.12	1.28	0.09	4.22	5.39	
TW	1.56	1	1.56	88.5	88.39	
NL	0.19	1.01	0.19	18.46	18.59	
FR	0.99	0.96	1.04	75.3	72.08	
CH	0.99	0.95	1.04	47.25	44.88	
IT	1.04	1	1.04	51.26	51.42	
JP	1.09	1.04	1.05	86.02	89.49	

Table C3 shows the results for the Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C3 shows the changes in efficiency for the period 2012-2013.

Table C3. Results of CRS MI DEA simulation for the period 2012-2013

	Period:	2012 to 2013	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	2	1	2	100	100	
ES	0.19	1.05	0.19	16.19	16.96	
DE	1.04	0.97	1.07	75.07	72.97	
TR	0.16	1.26	0.12	5.39	6.82	
TW	1.63	1.05	1.55	88.39	92.78	
NL	0.19	1.05	0.18	18.59	19.52	
FR	0.99	0.97	1.03	72.08	69.83	
CH	1.2	1.17	1.03	44.88	52.38	
IT	0.94	0.92	1.03	51.42	47.24	
JP	1	0.97	1.03	89.49	87.21	

Table C4 shows the results for the Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C4 shows the changes in efficiency for the period 2013-2014.

Table C4. Results of CRS MI DEA simulation for the period 2013-2014

	Period:	2013 to 2014	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	2.11	1	2.11	100	100	
ES	0.2	1.01	0.19	16.96	17.14	
DE	1.01	0.97	1.04	72.97	70.56	
TR	0.12	0.92	0.13	6.82	6.29	
TW	1.75	1.08	1.62	92.78	100	
NL	0.13	0.7	0.18	19.52	13.67	
FR	1	1	1	69.83	69.75	
CH	0.94	0.94	1	52.38	49.49	
IT	0.81	0.81	1	47.24	38.15	
JP	0.97	1.05	0.92	87.21	91.58	

Table C5 shows the results for the Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C5 shows the changes in efficiency for the period 2014-2015.

Table C5. Results of CRS MI DEA simulation for the period 2014-2015

	Period:	2014 to 2015	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	1.7	0.75	2.28	100	74.57	
ES	0.22	1.26	0.18	17.14	21.55	
DE	1.05	1.18	0.89	70.56	83.6	
TR	0.13	1.18	0.11	6.29	7.42	
TW	2.28	1	2.28	100	100	
NL	0.25	1.77	0.14	13.67	24.15	
FR	0.9	1.02	0.88	69.75	71.19	
CH	1.06	1.21	0.88	49.49	59.95	
IT	1.02	1.16	0.88	38.15	44.18	
JP	1.04	1.09	0.95	91.58	100	

Table C6 shows the results for the Circular Malmquist Productivity Index, EC-Technical (Managerial) Efficiency Catch Up and BS-Boundary Shift (Technological Change). Also, Table C6 shows the changes in efficiency for the period 2015-2016.

Table C6. Results of CRS MI DEA simulation for the period 2015-2016

	Period:	2015 to 2016	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	1.68	1.01	1.66	74.57	75.2	
ES	0.18	0.83	0.21	21.55	17.85	
DE	1.12	0.97	1.15	83.6	81.2	
TR	0.13	1.03	0.12	7.42	7.67	
TW	2.45	1	2.45	100	100	
NL	0.19	0.75	0.26	24.15	18.08	
FR	1.02	1.04	0.98	71.19	74.13	
CH	1.11	1.13	0.98	59.95	67.8	
IT	0.94	0.96	0.98	44.18	42.41	
JP	0.98	1	0.98	100	100	

Table C7 shows the changes in efficiency for the period 2016-2017. Where CMI -Circular Malmquist Index (or Malmquist Productivity Index), EC-Technical

(Managerial) Efficiency Catch Up, BS-Boundary Shift (Technological Change). CMI decomposed into different sources of EC and BS growth.

Table C7. Results of CRS MI DEA simulation for the period 2016-2017

	Period:	2016 to 2017	Selection:	Selection 1	Categorical	<All>
Name	CMI	EC	BS	First Efficie	Second Efficiency	
KR	1.21	0.68	1.79	75.2	50.83	
ES	0.16	0.92	0.18	17.85	16.35	
DE	0.69	0.64	1.08	81.2	51.59	
TR	0.13	1.2	0.11	7.67	9.19	
TW	2.74	1	2.74	100	100	
NL	0.23	1.1	0.21	18.08	19.96	
FR	0.83	0.84	0.99	74.13	62.16	
CH	0.94	0.95	0.99	67.8	64.52	
IT	1.01	1.03	0.99	42.41	43.53	
JP	0.99	1	0.99	100	100	

The technical efficiency shows the possibility of HSRs to produce maximum output with an input that is measured by input/output ratio. The OTE in the CRS model gives the same technical efficiency scores whether there is no difference in input or output oriented models.

Table C8 represents the percentage of efficiency of the selected HSRs in 2010. Two HSRs in 2010 were efficient KR and JP and three HSRs had an efficiency over 90%.

Table C8. Efficiency score of the selected HSR in 2010

	Period:	2010	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	100					
ES	23.38					
DE	92.97					
TR	7.26					
TW	95.37					
NL	20.75					
FR	94.36					
CH	54.4					
IT	55.62					
JP	100					

Table C9. represents the percentage of efficiency of the selected HSRs in 2011. Only one HSR in 2011 was efficient, and it was KR. The efficiency of HSRs in 2011 was sufficiently lower compared to 2010.

Table C9. Efficiency score of the selected HSRs in 2011

	Period:	2011	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	100					
ES	17.37					
DE	73.4					
TR	4.22					
TW	88.5					
NL	18.46					
FR	75.3					
CH	47.25					
IT	51.26					
JP	86.02					

Table C10 represents the percentage of efficiency of the selected HSRs in 2012. Only one HSR in 2012 was efficient, which was KR.

Table C10. Efficiency score of the selected HSRs in 2012

	Period:	2012	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	100					
ES	16.19					
DE	75.07					
TR	5.39					
TW	88.39					
NL	18.59					
FR	72.08					
CH	44.88					
IT	51.42					
JP	89.49					

Table C11 represents the percentage of efficiency of the selected HSRs in 2013. Only one HSR in 2013 was efficient, which was KR. The TW HSR showed improvement in efficiency and scored 92.78%.

Table C11. Efficiency score of the selected HSRs in 2013

	Period:	2013	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	100					
ES	16.96					
DE	72.97					
TR	6.82					
TW	92.78					
NL	19.52					
FR	69.83					
CH	52.38					
IT	47.24					
JP	87.21					

Table C12 represents the percentage of efficiency of the selected HSRs in 2014. Two HSRs in 2014 were efficient KR and TW.

Table C12. Efficiency score of selected HSRs in 2014

	Period:	2014	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	100					
ES	17.14					
DE	70.56					
TR	6.29					
TW	100					
NL	13.67					
FR	69.75					
CH	49.49					
IT	38.15					
JP	91.58					

Table C13 represents the percentage of efficiency of the selected HSRs in 2015. Two HSRs in 2015 were efficient TW and JP.

Table C13. Efficiency score of selected HSRs in 2015

	Period:	2015	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	74.57					
ES	21.55					
DE	83.6					
TR	7.42					
TW	100					
NL	24.15					
FR	71.19					
CH	59.95					
IT	44.18					
JP	100					

Table C14 represents the percentage of efficiency of the selected HSRs in 2016. Two HSRs in 2016 were efficient TW and JP.

Table C14. Efficiency score of selected HSRs in 2016

	Period:	2016	Selection:	Selection	Categorica	<All>
Name	Efficiency					
KR	75.2					
ES	17.85					
DE	81.2					
TR	7.67					
TW	100					
NL	18.08					
FR	74.13					
CH	67.8					
IT	42.41					
JP	100					

Table C15 represents the percentage of efficiency of the selected HSRs in 2017. Two HSRs in 2017 were efficient TW and JP.

Table C15. Efficiency score of selected HSRs in 2017

	Period:	2017	Selection:	Selection 1	Categorical	<All>
Name	Efficiency					
KR	50.83					
ES	16.35					
DE	51.59					
TR	9.19					
TW	100					
NL	19.96					
FR	62.16					
CH	64.52					
IT	43.53					
JP	100					

Lambda of the CRS MI DEA Output-Oriented Model

Lambda values represented for each of the individual HSR for each of the periods. Lambda defines the amount of outputs to be increased for an inefficient HSR to reach their peers which are operating efficiently. Table C16 shows the values of Lambda for the selected HSRs to reach their peers (KR and JP) in 2010.

Table C16. Lambda of CRS MI DEA for 2010

	Period:	2010	Selection:	Selection	Categorica	<All>
Name	KR	JP				
KR	1	0				
ES	4.56	0				
DE	2.34	0				
TR	0	0.09				
TW	0	0.13				
NL	0	0.05				
FR	5.01	0				
CH	0	1.78				
IT	1.86	0				
JP	0	1				

Table C17 shows the values of Lambda for the selected HSRs to reach their peer (KR HSR) in 2011.

Table C17. Lambda of CRS MI DEA for 2011

	Period:	2011	Selection:	Selection	Categorica	<All>
Name	KR					
KR	1					
ES	4.77					
DE	2.34					
TR	1.2					
TW	0.93					
NL	0.33					
FR	5.03					
CH	16.52					
IT	1.77					
JP	7.1					

Table C18 shows the values of Lambda for the selected HSRs to reach their peer (KR HSR) in 2012.

Table C18. Lambda of CRS MI DEA for 2012

	Period:	2012	Selection:	Selection	Categorica	<All>
Name	KR					
KR	1					
ES	4.9					
DE	2.34					
TR	1.2					
TW	0.96					
NL	0.33					
FR	5.03					
CH	22.88					
IT	1.77					
JP	7.1					

Table C19 shows the values of Lambda for the selected HSRs to reach their peer (KR HSR) in 2013.

Table C19. Lambda of CRS MI DEA for 2013

	Period:	2013	Selection:	Selection	Categorica	<All>
Name	KR					
KR	1					
ES	5.2					
DE	2.39					
TR	1.2					
TW	0.93					
NL	0.33					
FR	5.03					
CH	28.28					
IT	1.83					
JP	7.1					

Table C20 shows the values of Lambda for the selected HSRs to reach their peers (KR and TW HSRs) in 2014.

Table C20. Lambda of CRS MI DEA for 2014

	Period:	2014	Selection:	Selection	Categorica	<All>
Name	KR	TW				
KR	1	0				
ES	5.17	0				
DE	2.39	0				
TR	1.71	0				
TW	0	1				
NL	0	0.35				
FR	5.03	0				
CH	39.55	0				
IT	2.32	0				
JP	5.6	1.96				

Table C21 shows the values of Lambda for the selected HSRs to reach their peers (TW and JP HSRs) in 2015.

Table C21. Lambda of CRS MI DEA for 2015

	Period:	2015	Selection:	Selection	Categorica	<All>
Name	TW	JP				
KR	0.1	0.2				
ES	0	0.67				
DE	0	0.31				
TR	0	0.25				
TW	1	0				
NL	0	0.04				
FR	0	0.72				
CH	0	6.6				
IT	0	0.3				
JP	0	1				

Table C22 shows the values of Lambda for the selected HSRs to reach their peers (TW and JP HSRs) in 2016.

Table C22. Lambda of CRS MI DEA for 2016

	Period:	2016	Selection:	Selection	Categorica	<All>
Name	TW	JP				
KR	0.34	0.18				
ES	0	0.85				
DE	0	0.34				
TR	0	0.25				
TW	1	0				
NL	0.34	0				
FR	0	0.74				
CH	0	6.9				
IT	0	0.31				
JP	0	1				

Table C23 shows the values of Lambda for the selected HSRs to reach their peers (TW and JP HSRs) in 2017.

Table C23. Lambda of CRS MI DEA for 2017

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	TW	JP				
KR	0.43	0.24				
ES	0	0.94				
DE	0	0.55				
TR	0	0.24				
TW	1	0				
NL	0.34	0				
FR	0	0.93				
CH	0	8.84				
IT	0	0.29				
JP	0	1				

Peers of CRS MI DEA Output-Oriented Model

Table C24 shows the frequency of peers for the inefficient HSRs in 2010. The KR HSR appears 5 times and the JP HSR 5 times.

Table C24. Peers Frequency for the inefficient HSRs in 2010

	Period:	2010	Selection:	Selection	Categorica	<All>
Name	KR	JP				
(Frequenc	5	5				
KR	True	False				
ES	True	False				
DE	True	False				
TR	False	True				
TW	False	True				
NL	False	True				
FR	True	False				
CH	False	True				
IT	True	False				
JP	False	True				

Table C25 shows the frequency of peers for the inefficient HSRs in 2011. The KR HSR appears 10 times.

Table C25. Peers Frequency for the inefficient HSRs in 2011

	Period:	2011	Selection:	Selection	Categorica	<All>
Name	KR					
(Frequenc	10					
KR	True					
ES	True					
DE	True					
TR	True					
TW	True					
NL	True					
FR	True					
CH	True					
IT	True					
JP	True					

Table C26 shows the frequency of peers for the inefficient HSRs in 2012. The KR HSR appears 10 times.

Table C26. Peers Frequency for the inefficient HSRs in 2012

	Period:	2012	Selection:	Selection	Categorica	<All>
Name	KR					
(Frequenc	10					
KR	True					
ES	True					
DE	True					
TR	True					
TW	True					
NL	True					
FR	True					
CH	True					
IT	True					
JP	True					

Table C27 shows the frequency of peers for the inefficient HSRs in 2013. The KR HSR appears 10 times.

Table C27. Peers Frequency for the inefficient HSRs in 2013

	Period:	2013	Selection:	Selection	Categorica	<All>
Name	KR					
(Frequenc	10					
KR	True					
ES	True					
DE	True					
TR	True					
TW	True					
NL	True					
FR	True					
CH	True					
IT	True					
JP	True					

Table C28 shows the frequency of peers for the inefficient HSRs in 2014. The KR HSR appears 8 times and the TW HSR 3 times.

Table C28. Peers Frequency for the inefficient HSRs in 2014

	Period:	2014	Selection:	Selection	Categorica	<All>
Name	KR	TW				
(Frequenc	8	3				
KR	True	False				
ES	True	False				
DE	True	False				
TR	True	False				
TW	False	True				
NL	False	True				
FR	True	False				
CH	True	False				
IT	True	False				
JP	True	True				

Table C29 shows the frequency of peers for the inefficient HSRs in 2015. The TW HSR appears 2 times and the JP HSR 9 times.

Table C29. Peers Frequency for the inefficient HSRs in 2015

	Period:	2015	Selection:	Selection	Categorica	<All>
Name	TW	JP				
(Frequenc	2	9				
KR	True	True				
ES	False	True				
DE	False	True				
TR	False	True				
TW	True	False				
NL	False	True				
FR	False	True				
CH	False	True				
IT	False	True				
JP	False	True				

Table C30 shows the frequency of peers for the inefficient HSRs in 2016. The TW HSR appears 3 times and the JP HSR 8 times.

Table C30. Peers Frequency for the inefficient HSRs in 2016

	Period:	2016	Selection:	Selection	Categorica	<All>
Name	TW	JP				
(Frequenc	3	8				
KR	True	True				
ES	False	True				
DE	False	True				
TR	False	True				
TW	True	False				
NL	True	False				
FR	False	True				
CH	False	True				
IT	False	True				
JP	False	True				

Table C31 shows the frequency of peers for the inefficient HSRs in 2017. The TW HSR appears 3 times and the JP HSR 8 times.

Table C31. Peers Frequency for the inefficient HSRs in 2017

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	TW	JP				
(Frequenc	3	8				
KR	True	True				
ES	False	True				
DE	False	True				
TR	False	True				
TW	True	False				
NL	True	False				
FR	False	True				
CH	False	True				
IT	False	True				
JP	False	True				

Targets of CRS MI DEA Output-Oriented Model

Table C32 shows the targets value of input and outputs for the inefficient HSRs in 2010. These targets need to be reached to be on the frontier line.

Table C32. Targets values of input and output for the inefficient HSRs in 2010

	Period:	2010	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line Gain(%)	
KR	41349	41349	0	10981	10981	0	369	369	0	
ES	28056	188703.8	572.6	11715	50113.83	327.77	1684	1684	0	
DE	78506	96817.17	23.32	23903	25711.61	7.57	864	864	0	
TR	1890	26047.14	1278.16	476	6883.14	1346.04	232	232	0	
TW	36939	38733.89	4.86	7491	10235.7	36.64	345	345	0	
NL	2796	13472.66	381.85	285	3560.24	1149.21	120	120	0	
FR	112557	207081.2	83.98	51890	54994.28	5.98	1848	1848	0	
CH	285520	524872.2	83.83	46300	138701.2	199.57	4675	4675	0	
IT	33993	76758.98	125.81	11338	20384.78	79.79	685	685	0	
JP	294153	294153	0	77732	77732	0	2620	2620	0	

Table C33. Target values of input and output for the inefficient HSRs in 2011

	Period:	2011	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	50309	50309	0	13561	13561	0	369	369	0	
ES	28899	239819.9	729.86	11231	64644.44	475.59	1759	1759	0	
DE	76100	117796.7	54.79	23305	31752.59	36.25	864	864	0	
TR	2557	60534.41	2267.4	665	16317.3	2353.73	444	444	0	
TW	41629	47036.87	12.99	8148	12678.98	55.61	345	345	0	
NL	3020	16360.65	441.74	305	4410.08	1345.93	120	120	0	
FR	110384	253181.1	129.36	51386	68246.01	32.81	1857	1857	0	
CH	285520	830984.7	191.04	105842	223995.4	111.63	6095	6095	0	
IT	37941	88892.87	134.29	12283	23961.44	95.08	652	652	0	
JP	307284	357207.5	16.25	82078	96286.78	17.31	2620	2620	0	

Table C34. Target values of input and output for the inefficient HSRs in 2012

	Period:	2012	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	52362	52362	0	14083	14083	0	369	369	0	
ES	28393	256701.5	804.1	11177	69041.05	517.71	1809	1809	0	
DE	76600	122603.7	60.06	24753	32974.83	33.22	864	864	0	
TR	3350	63004.68	1780.74	914	16945.4	1753.98	444	444	0	
TW	44526	50375.37	13.14	8643	13548.69	56.76	355	355	0	
NL	3166	17028.29	437.85	324	4579.84	1313.53	120	120	0	
FR	110825	263512.8	137.77	51086	70872.98	38.73	1857	1857	0	
CH	372050	1197940	221.98	144610	322191.6	122.8	8442	8442	0	
IT	39665	92520.39	133.25	12794	24883.78	94.5	652	652	0	
JP	323535	371784.4	14.91	89483	99993.12	11.75	2620	2620	0	

Table C35. Target values of input and output for the inefficient HSRs in 2013

	Period:	2013	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	54744	54744	0	14451	14451	0	369	369	0	
ES	32123	284698.5	786.28	12744	75153.03	489.71	1919	1919	0	
DE	78770	130703.2	65.93	25178	34502.25	37.03	881	881	0	
TR	4207	65870.83	1465.74	1186	17388.2	1366.12	444	444	0	
TW	47490	51183.41	7.78	9118	13511.1	48.18	345	345	0	
NL	3475	17802.93	412.31	363	4699.51	1194.63	120	120	0	
FR	109796	275500.3	150.92	50786	72724.95	43.2	1857	1857	0	
CH	537920	1548410	187.85	214110	408740.1	90.9	10437	10437	0	
IT	39613	100141.5	152.8	12489	26434.76	111.66	675	675	0	
JP	335590	388697.2	15.83	89483	102606	14.67	2620	2620	0	

Table C36. Target values of input and output for the inefficient HSRs in 2014

	Period:	2014	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	49847	49847	0	14433	14433	0	369	369	0	
ES	34100	257745.5	655.85	12788	74629.17	483.59	1908	1908	0	
DE	77951	119011.4	52.67	24316	34459.28	41.71	881	881	0	
TR	5086	85374.81	1578.62	1555	24719.93	1489.71	632	632	0	
TW	48020	48020	0	9235	9235	0	345	345	0	
NL	2284	16702.61	631.29	242	3212.17	1227.34	120	120	0	
FR	108978	250856	130.19	50659	72634.37	43.38	1857	1857	0	
CH	703790	1971456	180.12	282495	570827.1	102.07	14594	14594	0	
IT	39961	115634.2	189.37	12773	33481.43	162.13	856	856	0	
JP	341876	373314.9	9.2	90613	98945.76	9.2	2743	2743	0	

Table C37. Target values of input and output for the inefficient HSRs in 2015

	Period:	2015	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	56951	76370.52	34.1	15102	20251.58	34.1	596	596	0	
ES	36261	242228.1	568.01	14129	65567.95	364.07	1908	1908	0	
DE	79451	111719.5	40.61	25280	30240.98	19.62	880	880	0	
TR	5693	91914.64	1514.52	1847	24880.08	1247.05	724	724	0	
TW	50560	50560	0	9655	9655	0	345	345	0	
NL	2423	15234.47	528.74	996	4123.77	314.03	120	120	0	
FR	108849	259366.9	138.28	49980	70207.2	40.47	2043	2043	0	
CH	961190	2380640	147.68	386306	644407.9	66.81	18752	18752	0	
IT	40340	108672.6	169.39	12997	29416.23	126.33	856	856	0	
JP	360930	360930	0	97699	97699	0	2843	2843	0	

Table C38. Target values of input and output for the inefficient HSRs in 2016

	Period:	2016	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	64617	85929.1	32.98	16324	21708.01	32.98	657	657	0	
ES	38829	310441.7	699.51	15059	84386.74	460.37	2503	2503	0	
DE	83422	123283.7	47.78	27213	33511.95	23.15	994	994	0	
TR	5898	89796.17	1422.49	1871	24409.11	1204.6	724	724	0	
TW	56590	56590	0	10488	10488	0	350	350	0	
NL	3507	19402.29	453.24	365	3595.89	885.17	120	120	0	
FR	108849	268644.4	146.8	54130	73025.04	34.91	2166	2166	0	
CH	1221282	2518386	106.21	464104	684567.6	47.5	20305	20305	0	
IT	41445	112741.3	172.03	12997	30646.24	135.79	909	909	0	
JP	365014	365014	0	99221	99221	0	2943	2943	0	

Table C39. Target values of input and output for the inefficient HSRs in 2017

	Period:	2017	Selection:	Selection	Categorica	<All>				
Name	(O) Numb	(O) Numb	(O) Numb	(O) HSR tr	(O) HSR tr	(O) HSR tr	(I) HSR lin	(I) HSR lin	(I) HSR line	Gain(%)
KR	59669	117394.4	96.74	14869	29253.66	96.74	887	887	0	
ES	40259	354266	779.97	15540	95027.59	511.5	2852	2852	0	
DE	86732	205951.3	137.46	28502	55243.95	93.82	1658	1658	0	
TR	7160	89932.89	1156.05	2218	24123.41	987.62	724	724	0	
TW	60570	60570	0	11103	11103	0	354	354	0	
NL	4098	20532.2	401.03	413	3763.73	811.31	120	120	0	
FR	108720	349545.8	221.51	58280	93761.44	60.88	2814	2814	0	
CH	1517800	3337579	119.9	577635	895265.2	54.99	26869	26869	0	
IT	41276	111298.2	169.64	12997	29854.39	129.7	896	896	0	
JP	377743	377743	0	101325	101325	0	3041	3041	0	

Slacks of CRS MI DEA Output-Oriented Model

Table C40. Slacks of the inefficient HSRs in 2010

	Period:	2010	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	68687.31	0	0			
DE	12371.05	0	0			
TR	0	323.12	0			
TW	0	2380.71	0			
NL	0	2186.96	0			
FR	87790.54	0	0			
CH	0	53587.76	0			
IT	15642.39	0	0			
JP	0	0	0			

Table C41. Slacks of the inefficient HSRs in 2011

	Period:	2011	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	73480.3	0	0			
DE	14111.99	0	0			
TR	0	574.09	0			
TW	0	3472.51	0			
NL	0	2757.76	0			
FR	106579.5	0	0			
CH	226733.5	0	0			
IT	14878.29	0	0			
JP	0	873.8	0			

Table C42. Slacks of the inefficient HSRs in 2012

	Period:	2012	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	81316.12	0	0			
DE	20560.64	0	0			
TR	896.28	0	0			
TW	0	3770.26	0			
NL	0	2837.21	0			
FR	109762.3	0	0			
CH	369011.8	0	0			
IT	15373.66	0	0			
JP	10248.98	0	0			

Table C43. Slacks of the inefficient HSRs in 2013

	Period:	2013	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	95264.94	0	0			
DE	22762	0	0			
TR	4191.12	0	0			
TW	0	3683.97	0			
NL	0	2839.81	0			
FR	118273.7	0	0			
CH	521510	0	0			
IT	16294.88	0	0			
JP	3891.71	0	0			

Table C44. Slacks of the inefficient HSRs in 2014

	Period:	2014	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	58742.12	0	0			
DE	8543.6	0	0			
TR	4522.34	0	0			
TW	0	0	0			
NL	0	1442.46	0			
FR	94604.48	0	0			
CH	549333.4	0	0			
IT	10885.82	0	0			
JP	0	0	0			

Table C45. Slacks of the inefficient HSRs in 2015

	Period:	2015	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	73952.94	0	0			
DE	16676.87	0	0			
TR	15226.87	0	0			
TW	0	0	0			
NL	5202.45	0	0			
FR	106466	0	0			
CH	777251.9	0	0			
IT	17370.66	0	0			
JP	0	0	0			

Table C46. Slacks of the inefficient HSRs in 2016

	Period:	2016	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	92854.08	0	0			
DE	20552.13	0	0			
TR	12850.73	0	0			
TW	0	0	0			
NL	0	1576.54	0			
FR	121799.7	0	0			
CH	716957.5	0	0			
IT	15016.2	0	0			
JP	0	0	0			

Table C47. Slacks of the inefficient HSRs in 2017

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	108081	0	0			
DE	37843.16	0	0			
TR	12059.3	0	0			
TW	0	0	0			
NL	0	1694.48	0			
FR	174636	0	0			
CH	985170.1	0	0			
IT	16486.3	0	0			
JP	0	0	0			

Weights of CRS MI DEA Output-Oriented Model

The DEA model calculates the combination of inputs

The weight describes the importance of different factors and always has a positive value. The maximum value of weight is 1. The tables below show the weight restriction of the selected models and relation to each individual HSRs. Table B48 shows that the size of HSR networks in TR and NL in 2010 have influenced in the analysis and the higher value of weight the stronger influence in the analysis on efficiency values. The size of TR and NL HSR networks contributes at least 0.06 and 0.04 respectively of the total output to determine HSR efficiency.

Table C48. Weights of the CRS MI DEA Output-Oriented Model for 2010

	Period:	2010	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.06			
TW	0	0	0			
NL	0	0	0.04			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C49 shows that the size of HSR networks in TR and NL in 2011 have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of the TR and NL HSR networks contribute at least 0.06 and 0.05 respectively of the total output to determine an HSR efficiency.

Table C49. Weights of the CRS MI DEA Output-Oriented Model for 2011

	Period:	2011	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.05			
TW	0	0	0			
NL	0	0	0.05			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C50 shows that the size of HSR network in TR and NL in 2012 have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on efficiency values. The size of TR and NL HSRs network contribute at least 0.04 and 0.04 respectively of the total output to determine an HSR efficiency.

Table C50. Weights of the CRS MI DEA Output-Oriented Model for 2012

	Period:	2012	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.04			
TW	0	0	0			
NL	0	0	0.04			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C51 shows that the size of HSR networks in TR and NL in 2013 have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of TR and NL HSR networks contribute at least 0.03 and 0.04 respectively of the total output to determine an HSR efficiency.

Table C51. Weights of the CRS MI DEA Output-Oriented Model for 2013

	Period:	2013	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.03			
TW	0	0	0			
NL	0	0	0.04			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C52 shows that the size of HSR networks in TR and NL in 2014 have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of TR and NL HSR networks contribute at least 0.03 and 0.06 respectively of the total output to determine an HSR efficiency.

Table C52. Weights of the CRS MI DEA Output-Oriented Model for 2014

	Period:	2014	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.03			
TW	0	0	0			
NL	0	0	0.06			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C53 shows that the size of HSR network in TR and NL have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of TR and NL HSR networks contribute at least 0.02 and 0.03 respectively of the total output to determine an HSR efficiency.

Table C53. Weights of the CRS MI DEA Output-Oriented Model for 2015

	Period:	2015	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.02			
TW	0	0	0			
NL	0	0	0.03			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C54 shows that the size of HSR network in TR and NL have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of the TR and NL HSR networks contribute at least 0.02 and 0.05 respectively of the total output to determine an HSR efficiency.

Table C54. Weights of the CRS MI DEA Output-Oriented Model for 2016

	Period:	2016	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.02			
TW	0	0	0			
NL	0	0	0.05			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Table C55 shows that the size of HSR networks in TR and NL in 2017 have influenced in the analysis and the higher value of weight, the stronger influence in the analysis on the efficiency values. The size of TR and NL HSRs network contribute at least 0.02 and 0.04 respectively of the total output to determine an HSR efficiency.

Table C55. Weights of CRS MI DEA Output-Oriented Model for 2017

	Period:	2017	Selection:	Selection	Categorica	<All>
Name	(O) Numb	(O) HSR tr	(I) HSR line			
KR	0	0	0			
ES	0	0	0			
DE	0	0	0			
TR	0	0	0.02			
TW	0	0	0			
NL	0	0	0.04			
FR	0	0	0			
CH	0	0	0			
IT	0	0	0			
JP	0	0	0			

Production Possibility Set (PPS) Chat of the selected period 2010-2017 CRS MI model

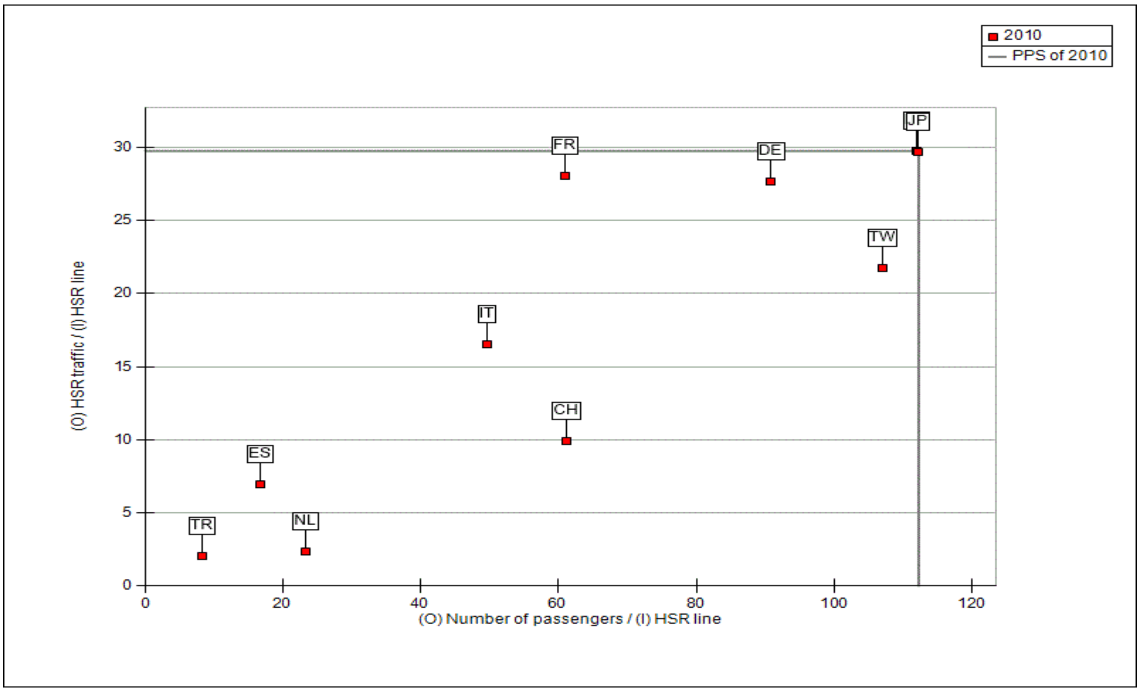

Figure C1. PPS Chat of 2010

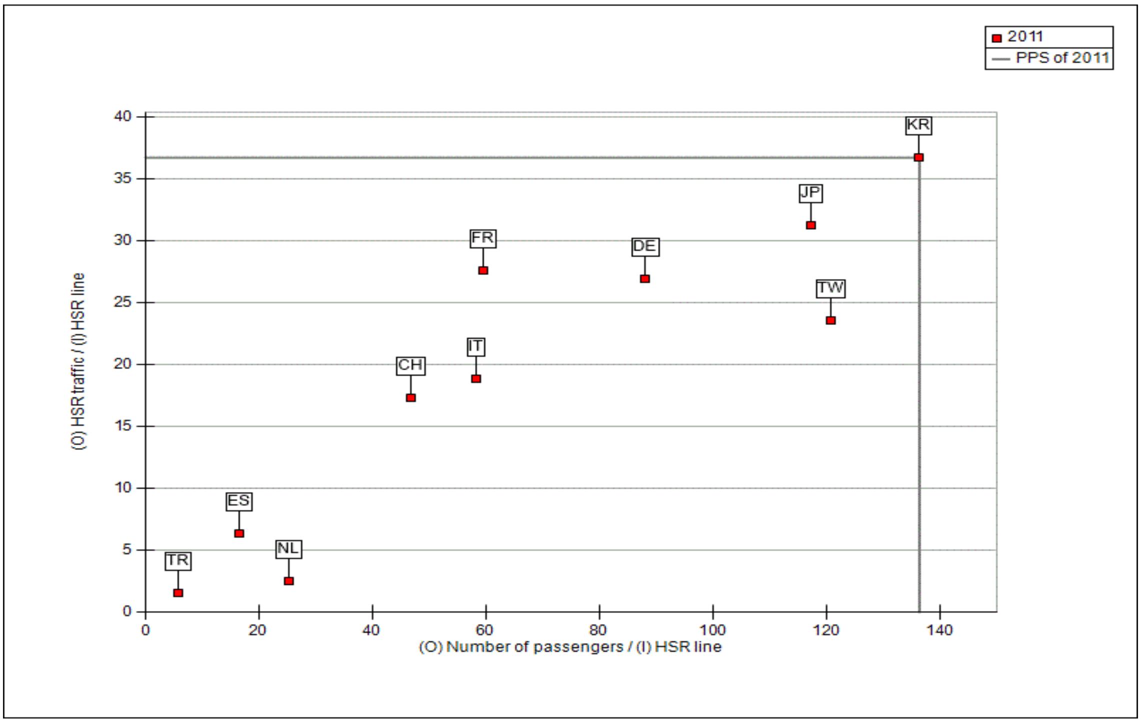

Figure C2. PPS Chat of 2011

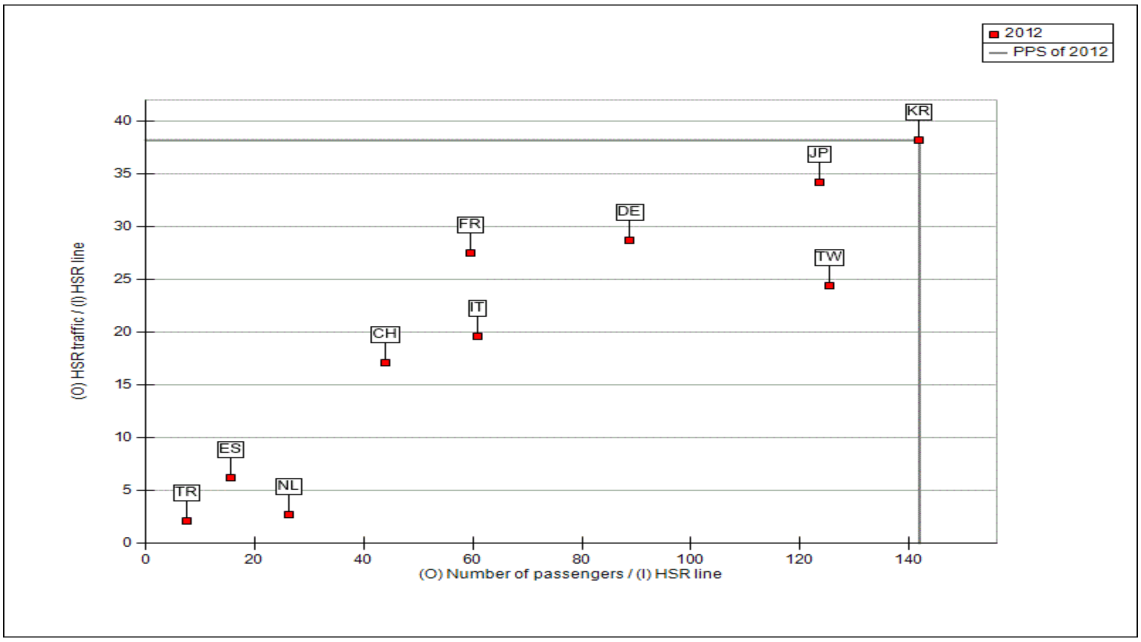

Figure C3. PPS Chat of 2012

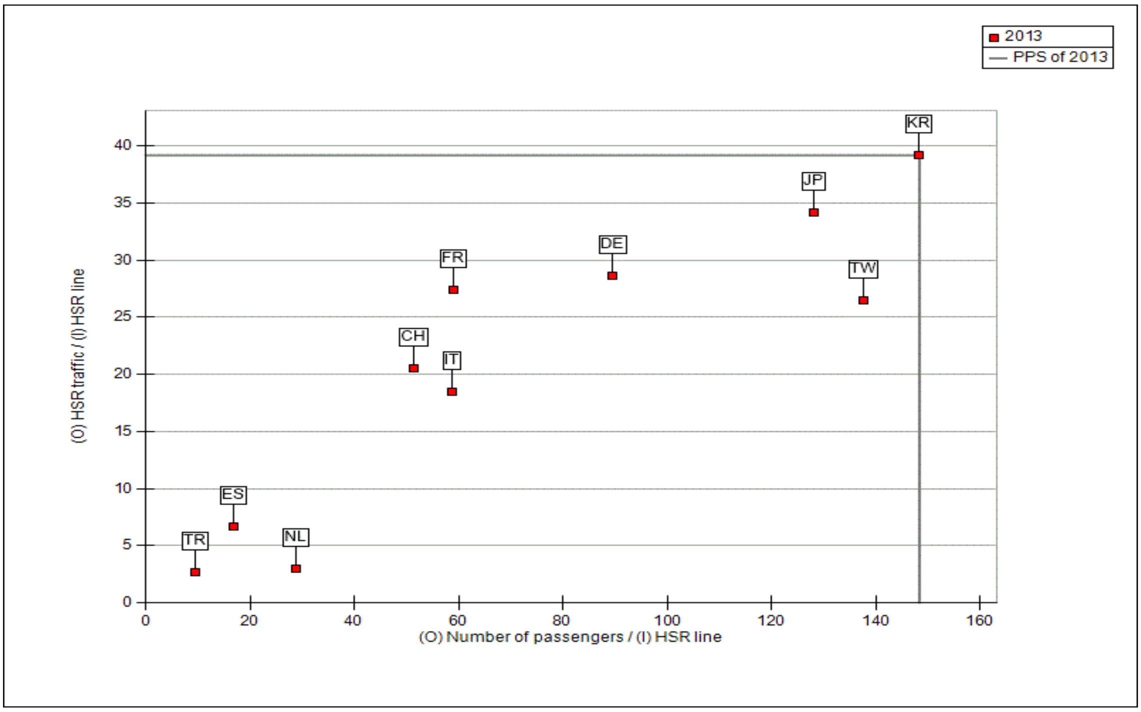

Figure C4. PPS Chat of 2013

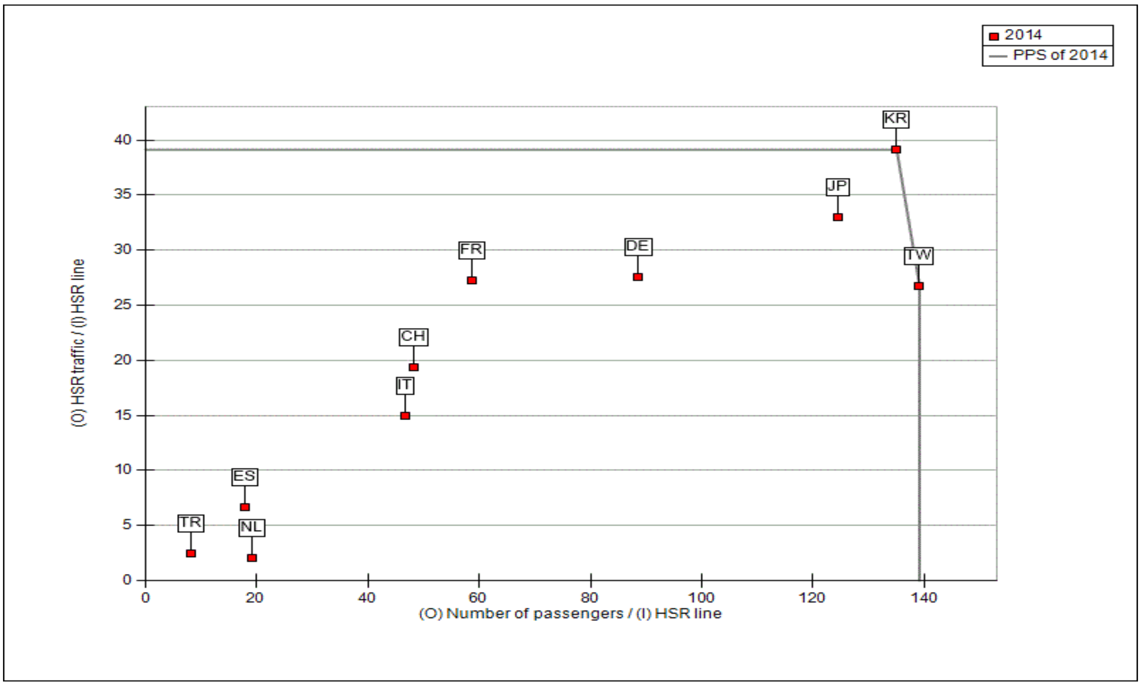

Figure C5. PPS Chat of 2014

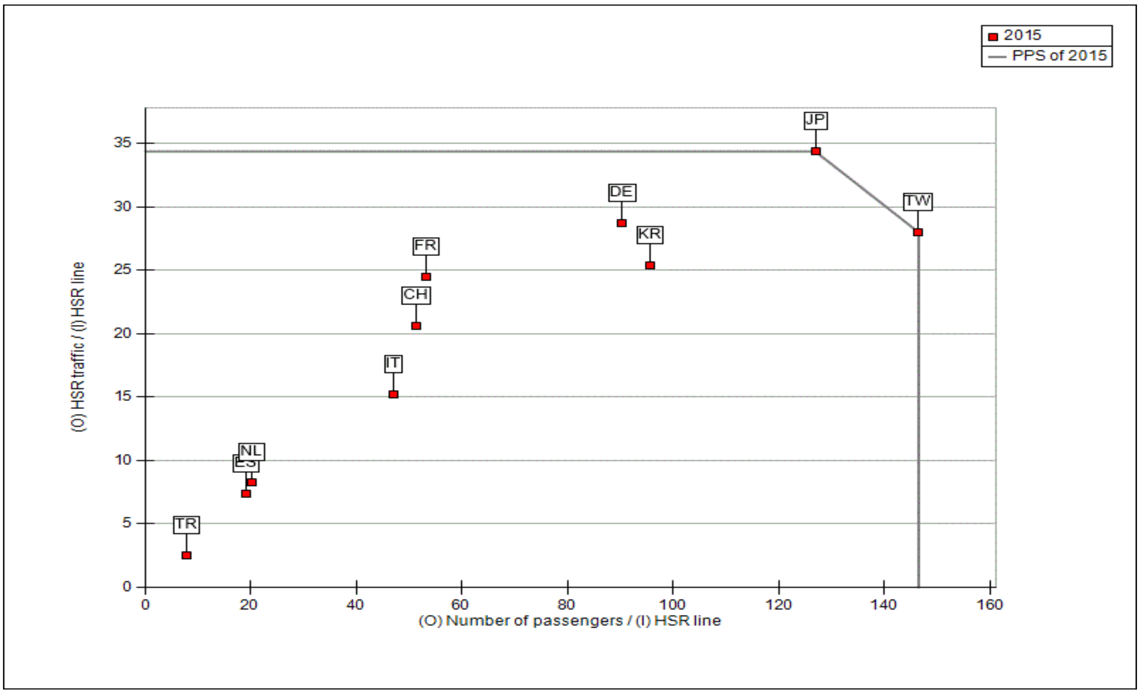

Figure C6. PPS Chat of 2015

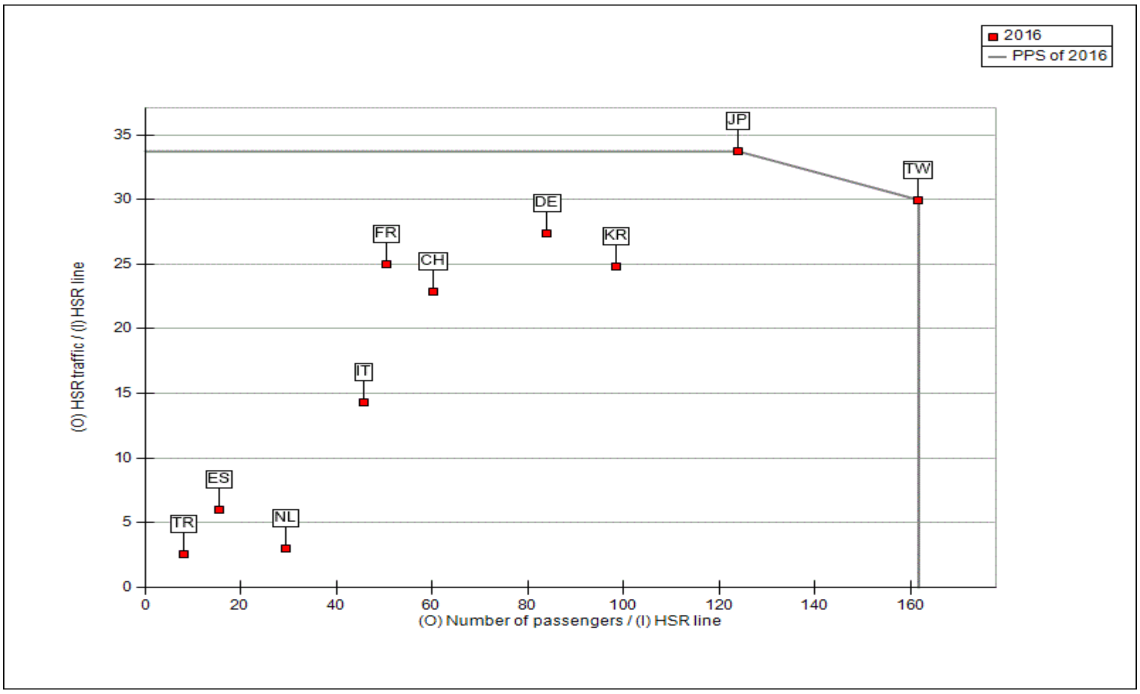

Figure C7. PPS Chat of 2016

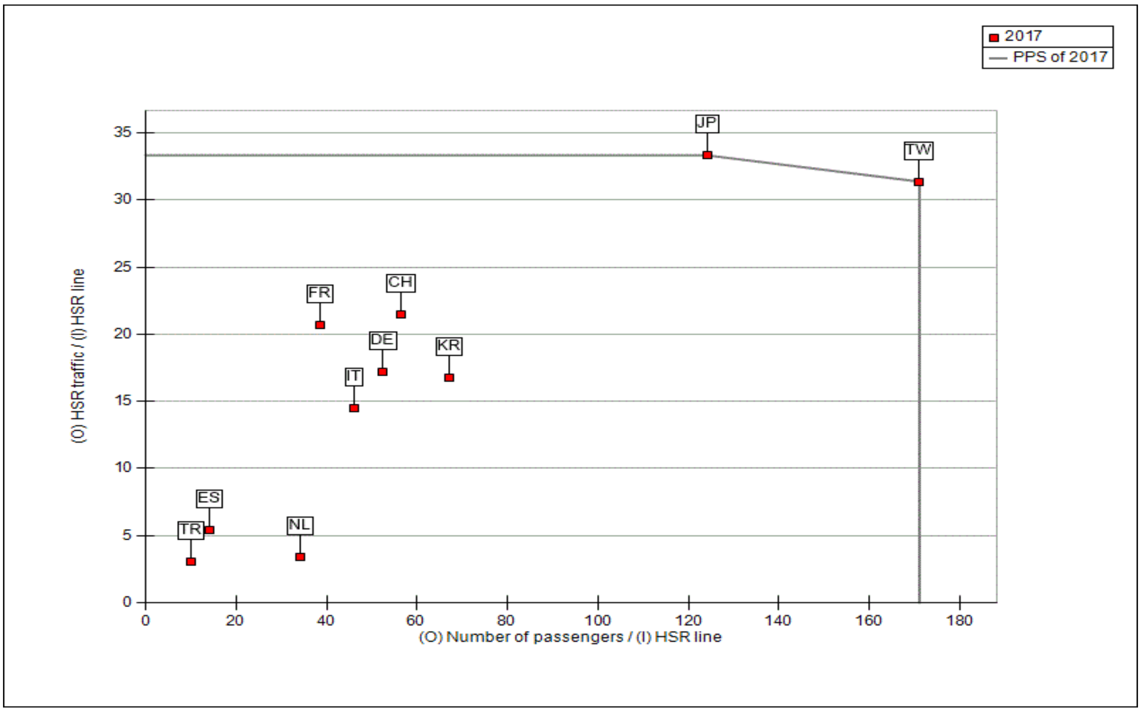

Figure C8. PPS Chat of 2017

Appendix D

Summary of transport projects that applied the DEA models

Table D1 Summary of transport projects that applied the DEA approach (Source: Author’s creation)

Author (s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Oum et al. (2013)	Measurement and comparison of social efficiency across firms in different transport modes	Japan	DEA, DODF S-TFR, ASC,	45	Number of employees, capital cost, variable cost passenger’s time	Passenger-km., life-cycle CO2 emissions
Yu M-M & Lin E.T.J. (2008)	Estimation of efficiency and effectiveness in railway performance	World Wide	MNDEA	20	Number of employees, length of line, the number of passenger cars, the number of freight cars	Passenger t-km, freight train-km
Wang & Lan (2013)	Estimating the most productive scale size with double frontiers DEA	China	DEA, MPSS	31	Number of employees, original value of fixed assets, current assets,	Gross industrial output value
Yu M-M (2008)	Investigation of un-storable feature of transportation services	World Wide	Two-stage DEA	40	Number of employees, the number of passenger cars, the number of freight cars, length of railway line	P-tr-km, P-km, f-tr-km, ton-km,
Song et al., (2016)	Rail transport-on and environmental efficiency	China	Non-radial DEA	30	Nb employees, energy consumption, capital stock	GDP, carbon and sulphur dioxide emissions
Doomernik, (2015)	Comparing four Asian and four European HSR systems to investigate production efficiency and service effectiveness, explores the differences between Europe and Asia. From the resulting performance matrices, strategies are proposed to improve overall efficiency.	Asia & Europe	NDEA, Malmquist Productivity Index All efficiency and effectiveness scores and The Malmquist Productivity Index are calculated by using (Data Envelopment Analysis Program) software written by Tim Coelli (2001).	48	Railway network length, rolling stock capacity	Travel volume, ridership

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Oum et al., (2013)	Measurement and comparison of social efficiency across firms in different transport modes	Japan	DEA, DODF S-TFR, ASC,	45	Number of employees, capital cost, variable cost passenger's time	Passenger-km., life-cycle CO2 emissions
Sameni et al., (2016)	Evaluation and efficiency of passenger railway stations	UK	Two-stage DEA, Tobit regression	96	Stage1: number of platforms, percentage of through lines, station staff, length of platform Stage 2: Number of trains stop, station catchment area of population, opportunities for jobs in the catchment area	Stage 1: number of trains stops Stage 2: number of passenger entries and exits, number of passenger interchanges
Yu M-M & Lin E.T.J. (2008)	Estimation of efficiency and effectiveness in railway performance	World wide	MNDEA	20	Number of employees, length of line, number of passenger cars, number of freight cars	Passenger t-km, freight train-km
Cesaroni, (2018)	Provide a method of implementation in DEA "cost minimizing industry structure"	Italy	DEA	43	Number of employees, vehicles, composite of consumption of fuel, energy, materials and spare parts	Vehicle-km, size of transport network
Wang & Lan (2013)	Estimating most productive scale size with double frontiers DEA	China	DEA, MPSS	31	Number of employees, original value of fixed assets, current assets,	Gross industrial output value
Yu M-M (2008)	Investigation of un-storable feature of transportation services	World wide	Two-stage DEA	40	Number of employees, passenger cars, of freight cars, length of railway line	P-tr-km, P-km, f-tr-km, ton-km,
Song et al., (2016)	Rail transport-on and environmental efficiency	China	Non-radial DEA	30	Employees, energy consumption, capital stock	GDP, carbon and sulphur dioxide emissions

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Pjevcevic et al., (2011)	Analysis of AGV fleet operations in a port container terminal	Serbia	DEA	12	Number of AGVs, AGV active rate	Number of containers in queue, number of served containers
Mohajeri & Amin, (2010)	Find the optimum site for a railway station	Iran	DEA, AHP	5	Dummy input (=1)	Four Priorities: Rail-related, Passenger services, Architecture and urbanism, Economics
Jitsuzumi & Nakamura, (2010)	To analyse the reasons for the underperformance of Japanese railway services and optimum subsidy level method	Japan	DEA, TFP	53	Related fixed assets, number of employees, operational expenditures (labour cost, tax and depreciation) Environmental/ uncontrollable factors- transport density	P-km, GDP per capita
Guo et al., (2017)	To calculate and analyse past, present and future efficiency for CO_2 emissions.	Worldwide	DEA-dynamic model, Solver software	27	Land area, population, energy use, carry-over variable: energy stock	CO_2 emissions, GDP
Doomernik, (2015)	Compared four Asian and Four European HSR systems to investigate the production efficiency and service effectiveness. study also explores the differences between two regions, Europe and Asia, and strategies are proposed to improve the overall efficiency.	Asia & Europe	NDEA, Malmquist Productivity Index All efficiency and effectiveness scores and The Malmquist Productivity Index are calculated by using (Data Envelopment Analysis Program) software written by Tim Coelli (2001)	48	Railway network length, rolling stock capacity	Travel volume, ridership

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Qiang & Ye (2014)	Evaluate transportation energy efficiency	China	Three stage virtual frontier DEA model	30	Number of employees, capital, energy	Passenger-km, tonne-km
Chen et al., (2016)	Investigate the impact of HSR investment from two perspectives economy and environment.	China	Computable general equilibrium (CGE) model	48	Annual capital spending on rail infrastructure construction, capital spending on rail related equipment manufacturing, rail transport cost, productivity, direct land use for railway development, extended land use, substitution demand and induced demand	CO_2 emission, change in GDP
Azadeh et al, (2008)	Railway improvement and optimization	Iran	DEA and AHP integrated with computer stimulation	22	Qualitative and quantitative variables	Qualitative and quantitative variables
Po-Lin Lai et al., (2015)	Analysing the airports productivity	Worldwide	AHP/DEA-AR	24	Length of runway, size of terminal area, number of runways, number of gates, number of employees, operational expenditure	Aircraft movements, amount of freight and mail, number of passengers, total revenues
Coelli & Perelman (1999)	A comparison of parametric and non-parametric distance functions: with application to European railways	Europe	(VRS)DEA, COLS, PLP	102	Labour, equipment, capital	Passenger services, freight services
Lan & Lin (2006)	Evaluated technical efficiency and service effectiveness 39 worldwide railway systems by two stochastic distance function approaches.	Worldwide	SIDF, SCDF	312	Number of passenger cars, number of freight cars, number of employees	Passenger train-km, freight train-km,

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Gale & Pang (2000)	The study computes the DEA-based production efficiency and uses it to estimate the relation between energy efficiency and productivity	USA	DEA	126	Capital cost, labour, cost of fuels, cost of materials	Consumption of electricity
Karlaftis, (2004)	Investigate the relationship between efficiency and effectiveness and relationship between performance and scale economies	USA	DEA	1280	Number of employees, fuel, capital	Vehicle-km, passenger-km
Chang et al., (2013)	The authors analysed the environmental efficiency of China's transportation sector using the proposed a non-radial DEA model with the slacks-based measure (SBM).	China	SBE-DEA	30	Labour, capital, energy	CO_2 emission, GDP
Chang et al., (2014)	The study examined the economic and environmental efficiency global airlines in 2010.	World wide	SBE-DEA	27	Tonne-km, fuel consumption, number of employees	Revenue passenger-km (RPK), revenue ton-km (RTK), CO_2
Ha, (2011)	Social efficiency benchmarking, comparison of rail and air	Japan	Nonparametric DEA	36	Number of employees, capital, users' time cost, other variable inputs	p-km, carbon dioxide emission
Djordjevic et al., (2018)	Evaluate railway efficiency of European countries regarding the level of safety at LC through considering desirable and undesirable inputs, as well as desirable and undesirable outputs.	Europe	Non-radial DEA	25	Undesirable inputs- number of LC for each country Desirable input- total number of locomotives and railcars.	Desirable outputs- railway passenger volume and railway freight volume, Undesirable outputs- number of accidents at LC.

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Loizides & Tsionas (2002)	Developed a model to represent the cost structure of European railways based on general index of technical change.	Europe	TCI, SUR approach	230	Labour, capital, energy	Passenger-km, tonne-km
Banos-Pino et al., (2002)	Study the efficiency of regulated railway firms by applying an empirical application of the distance function; the case of RENFE	Spain	ITSUR	40	Labour, capital, energy	Passenger-km, tonne-km
Oum et al., (2013)	The study measure and compares social efficiency of major three passenger railway firms and two domestic airlines	Japan	Nonparametric directional output distance function (DODF) which is derivative model of DEA, social total factor productivity index (S-TFP) and composite social efficiency index	5	Labour, capita cost, variable cost, passengers' time	Passenger-km, life-cycle CO2 emissions
Zhang et al., (2016)	Evaluated performance 13 transit operator.	China	Super efficiency data envelopment analysis (SF-DEA), combine evaluation method (CEM)	13	Number of standard vehicles, labour, government subsidies	Passenger satisfactions, operational revenue
Song et al., (2016)	Evaluated the changes in the environmental efficiency of the transport sector.	China	An undesirable-output oriented DEA model with slack-based measure (SBM)	30	Labour, capital, energy consumption	Desirable output-GDP by transport sector, undesirable output-CO2 emissions
Liu et al., (2015)	Constructed the production possibility sets (PPS) and DEA model with undesirable variables	China	Two stage DEA model with undesirable variables	16	Labour, assets, Profit, loans, non-performing loans-second stage	Profit, loans, Market value, earnings per share, volatility-second stagge
Amirteimoori et al., (2006)	Presented DEA model to increase undesirable inputs and decrease undesirable outputs	Iran	DEA	14	Labour, square meters of premises, number of customers	Amount of deposits, amount of loans, amount of charges, amount of overdue debts

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Pestana Barros & Peypoch, (2010)	Proposed framework for benchmarking bus companies	Portugal	DEA, Malmquist index	11	Liquid assets, labour, fuel costs, vehicle capacity	Sales, number of passengers
Bi & Wu, (2014)	Classify the environmental performance of industry	China	Non-radial slack based SBM-DEA	31	Total assets, labour, electricity consumption	GDP, profits-desirable outputs SO2 emissions and volume of solid waste-undesirable outputs
Lee et al., (2014)	Assessed ports' environmental performance	Worldwide	Slack based (SBM-DEA)	27	Labour population in respective port cities	Gross regional domestic product (GRDP), container throughput-desirable output NO, SO2, CO2-undesirable outputs
Marchesi & Wanke (2017)	Assessed efficiency of Brazilian rail	Brazil	Two-stage DEA	60	Labour, number of wagons	Tonne-km
Pels et al., (2003)	Assessed European airports efficiency	Europe	DEA	34	Air transport movements (ATM)	Air passenger movements (APM)
Hernandez-Sancho et al., (2011)	Assessed energy efficiency in Spanish wastewater treatment plants	Spain	Non-radial DEA model	177	Energy, labour, reagents, maintenance cost waste management, other	Pollutant removed from wastewater-suspended solids (SS) and organic matter (COD)
Sueyoshi & Yuan (2017)	The study examines the level of economic achievement and environmental protection	China	DEA	30	Labour, capital, energy	Desirable output-GDP Undesirable outputs-CO2, SO2, dust, wastewater, Chemical Oxygen Demand and ammonia nitrogen
Sueyoshi et al., (2017)	The study compares radial, non-radial and intermediate DEA approach	China	DEA	30	Labour, capital, energy	Desirable output-GDP Undesirable outputs-CO2, SO2, dust, wastewater
Sueyoshi & Goto (2015)	Environmental assessment of petroleum companies	Worldwide	DEA	17	Amount of oil reserve, amount of gas reserve, the total operational cost, labour	Desirable outputs-amount of oil and gas production Undesirable output-amount of CO2

Author(s)	Purpose of the study	Country of study	Method (s)	N of DMUs	Inputs	Outputs
Watanabe & Tanaka (2007)	Efficiency analysis of Chinese industry	China	DDFA DEA	26	Labour, capital, material	Desirable output- Industrial value added Undesirable output- SO2
Yu & Fan (2009)	Proposed a mixed structure network data envelopment analysis (MSNDEA)	Taiwan	Mixed structure network data envelopment analysis (MSNDEA)	23	Labour, vehicles, fuel and network length, population density and car ownership	Vehicle-km, passenger-km, number of passengers
Zhang N. et al., (2015)	Proposed non-radial, Malmquist CO2 emission performance index (NMCPI)	China	NMCPI DEA	30	Capital stock, labour, energy	Gross product value- desirable output CO2- undesirable output
Zhou et al., (2007)	Presented a non-radial DEA method to measure environmental performance of OECD (Organization for Economic Cooperation and Development) countries	Worldwide	Non-radial DEA approach	26	Labour, energy consumption	GDP-desirable output, CO2, Sox, NOx, CO- undesirable outputs
Sun et al., (2017)	Study evaluated environmental performance of the Chinese port enterprises	China	DEA	17	Fixed assets, operational costs, labour	Desirable outputs- net profit, cargo throughput Undesirable output- NO emissions
Growitsch & Wetzel (2007)	Investigate the performance of European railways	Europe	DEA	152	Number of employees, number of rolling stocks, network length	Train-km, passenger-km
Graham (2008)	Estimate productivity and efficiency of urban railways by applying parametric and non-parametric methodology	Worldwide	DEA, TFP	89	Labor, fleet capacity, route length	Number of passengers, passenger-km, train-km