**UNIVERSITY OF SOUTHAMPTON**

FACULTY OF ENGINEERING AND PHYSICAL SCIENCE

School of Engineering

# Examining the factors impacting High-Speed Rail accessibility

by

**EMINE TUGBA YAZICI**

ORCID ID [0009-0002-3926-3636]

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## ABSTRACT

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Since the introduction of the first dedicated High-Speed Rail (HSR) route in 1964 in Japan, the system has captured the attention of countries worldwide as a safe and efficient long-distance transportation option. The literature surrounding High-Speed Rail systems has extensively investigated various dimensions of this subject. Particularly, HSR systems have been analysed within the realm of transport geography with a focus on the enhanced accessibility they bring to cities within the network. Many existing studies tend to assess accessibility changes by exclusively focusing on the travel duration between stations. They assume that HSR systems affect accessibility beyond the immediate vicinity of stations, but do not actually quantify or test this. This assumption might result in an overestimation of the spatial impact of accessibility. To addresses this issue, this thesis adopts a door-to-door journey time approach that considers intra and inter city part of the journey simultaneously.

Through a door-to-door journey time approach, the empirical evaluations carried out in the research provide insights into the implications of station location on inter-city accessibility. By analysing station location scenarios in real-world contexts, the study reveals the trade-offs between central and peripheral station options, emphasising the significance of access time to the station in determining overall accessibility benefits. Moreover, the research assesses how the integration level of new HSR stations with existing transport infrastructure influences accessibility outcomes. By examining scenarios that involve both construction of new stations and integration with established ones, the study highlights the importance of careful planning to ensure equal distribution of accessibility benefits across regions. This research used a case study of the High speed two corridor in the UK to reveal the diverse impacts of different design strategies on inter-city accessibility of HSR.

The results based on the examination of station location reveals that central stations, often associated with dense urban cores, offer proximity to transit connections, thereby reducing intra-city travel times. Conversely, peripheral stations, while providing accessibility to outlying areas, entail longer overall journey times due to increased distance from urban centres. Improving the

current central station rather than building a new peripheral HSR station can be preferable in terms of average travel times, and also the expected construction costs. In assessing the integration level of stations, despite the similarity in average journey time benefits between the two scenarios, spatial representation highlights which regions experience either gains or losses in terms of accessibility improvements. This study suggests that the accessibility benefits of High-Speed Rail (HSR) vary spatially, necessitating a more comprehensive evaluation. Therefore, policymakers and transportation planners should consider the spatial impact when assessing the benefits of new investments.

# Table of Contents

# List of Tables

# List of Figures

List of Figures

# Research Thesis: Declaration of Authorship

I, Emine Tugba Yazici, declare that this thesis entitled *Examining the factors impacting the High-speed rail accessibility* and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Signature:

Date:

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This thesis is dedicated to Prof. Özgen Korkmaz

# Abbreviations

| | |
|---|---|
| API | Application Programming Interface |
| CBA | Cost Benefit Analysis |
| DA | Daily Accessibility |
| D2D | Door-to-door |
| GDP | Gross Domestic Product |
| GJT | Generalised journey time |
| GTC | Generalised Transport Cost |
| GTFS | General Transit Feed Specification |
| HS2 | High Speed Two |
| HSR | High-Speed Rail |
| HST | High-Speed Train |
| HPC | High-performance computing |
| LSOA | Lower Layer Super Output Area |
| LUTI | Land Use and Transportation Interaction |
| MaaS | Mobility as a Service |
| MSOA | Middle Layer Super Output Area |
| OA | Output Area |
| OD | origin-destination |
| OTP | OpenTripPlanner |
| PA | Potential accessibility |
| sd | standard deviations |
| UIC | International Union of Railway |
| VTT | Value of travel time |
| WATT | Weighted Average Travel Time |

# Chapter 1 INTRODUCTION

## 1.1 Introduction

This chapter provides a comprehensive investigation into High-Speed Rail (HSR) studies, going into the background and context of the subject in section 1.2. The subsequent section, 1.3, outlines the problem statement that forms the basis of this research. Then, the aim and objectives of the research are presented in section 1.4. Highlighting the broader implications of the research, section 1.5 emphasises the significance and potential contributions of the findings. Lastly, the thesis structure is outlined in section 1.6.

## 1.2 Background to the study

Since the introduction of the first dedicated High Speed Rail route in 1964 in Japan, the system has captured the attention of countries worldwide as a safe and efficient long-distance transportation option. China has notably taken the lead, constructing the largest and most extensive HSR network globally. HSR development is much more advanced in many European countries (e.g. France, Spain, Germany) than it is in Australia and most Asian nations other than China and Japan. Countries like Australia and various Asian nations are also supportive of HSR development and have initiated research to understand its potential effects (Bharule et al., 2019; Department of Infrastructure and Transport, 2011).

While the HSR development holds a promising future, it demands substantial investment for constructing the necessary infrastructure. To ensure its success and efficiency, a careful transportation planning process becomes crucial. This involves a comprehensive understanding of transportation issues, developing effective solutions, and proactively addressing potential challenges to avoid future complications (Bruun, 2014). In general, the long-range transportation planning process can be grouped into five major phases (Bruun, 2014; Janos and Kriz, 2018; Vuchic, 2005). The process starts with setting goals and objectives, and ends up with the performance evaluation of alternative plans to select the best option, as shown in Figure 1.1.

The initial step of the transport planning process is the definition of goals and objectives for the transport system. These goals are crucial in delineating the desired conditions concerning mobility, travel opportunities, and transit service performance (Vuchic, 2005). They hold a critical role as reference points to assess current conditions and trends, providing direction for policy formulation and investment choices (Bruun, 2014).

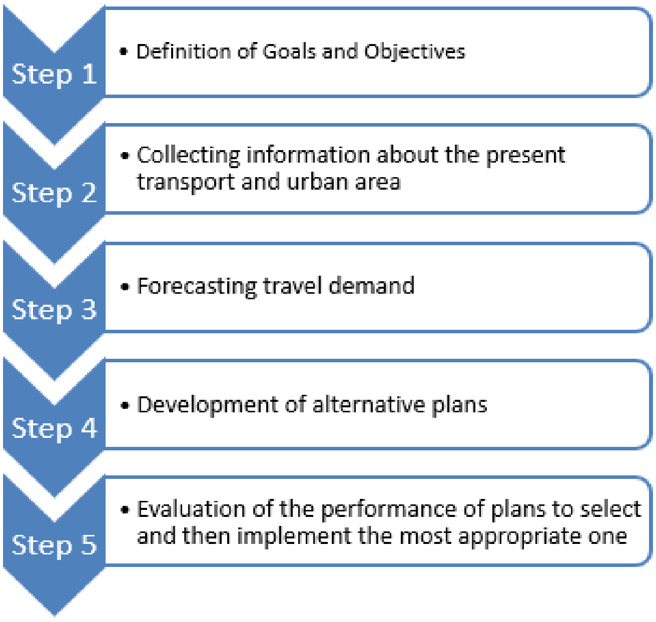


Figure 1.1 Theorical procedure of transit planning

*Source: adopted from Vuchic (2005)*

Transportation goals are dynamic entities, continually evolving in response to current trends and existing conditions (Litman, 2013). The earliest transport studies were focused on issues of cost efficiency in infrastructure provision and mobility, whereas the new consideration is more comprehensive, including accessibility, sustainability (encompassing economic, social, and environmental dimensions), macro-economic impact, seamless connectivity, intermodality, equity, integrated transport and land use strategies such as transit-oriented development and contributions to wider economic benefit (Meyer, 2000).

The inclusion of these goals in the planning process varies depending on the strategic priorities of a country, region, or urban area. Some argue that since public transport systems, such as High-Speed Rail, are funded by public funds, planning goals should align with the inputs and needs of the public (Bruun, 2014). This highlights the importance of considering public perspectives and requirements when shaping transport initiatives. Moreover, it is increasingly recognised that solutions must not only address project goals encompassing technical and ecological issues but also be assessed for their economic viability during implementation.

Following the establishment of clear goals and objectives, the second phase of the planning process entails an exhaustive gathering of information concerning the existing state of transportation and urban areas. This data collection encompasses a wide range of elements, including vital infrastructure elements such as land use and transportation systems, along with comprehensive data on the general population, economic indicators, and social factors. Additionally, the process makes a detailed analysis of travel volume, travel characteristics, modes of transportation used by the public, and the range of services provided by the transportation system.

The third phase is dedicated to the meticulous development of analytical computer-based models, specifically designed for travel forecasting. For example; High Speed Two (HS2) used the PLANET Framework Model based on the specialist transport modelling EMME/4 software platform (DfT, 2023a). These sophisticated models play a crucial role in accurately predicting both current and future travel patterns, considering the existing transportation networks as well as newly constructed infrastructure. Through these models, planners can validate and assess the efficacy of proposed designs, using the trip projections generated by the forecasting process (Vuchic, 2005).

The most critical and creative phase of planning is phase 4, in which alternative plans are developed in response to current situations, expected changes, and future objectives. The process of developing alternate plans is quite complex and needs specialised knowledge of transit systems (Vuchic, 2005). Given the absence of a precise methodology for the development of an optimal transit network, planners typically engage in the development and evaluation of several alternative plans. The alternative design or plans may differ among themselves with respect to several element and characteristics. In the case of High-Speed Rail planning, these alternatives designs may diverge with regards to detailed line designs, station locations, right of way alignment, structural specifications, rolling stock choices, and operational strategies.

The final phase of the planning process results in the critical evaluation and selection of the most preferable plan, guided by the criteria derived from the chosen goals and objectives for the future transportation system. Through an evaluation process, the preferred plan emerges as the most viable and effective option, meeting the defined goals and objectives most comprehensively. Upon the selection of the final plan, preparations for its implementation can commence.

When applying the general planning process to the planning of High-Speed Rail systems, the first step entails identifying and targeting the key goals that serve as the driving force for constructing or upgrading rail networks into high-speed systems. While the main goal usually differs based on each country's specific strategy, in almost all cases, HSR is designed to achieve a significant reduction in journey time, with high speed being the primary planning motivation (Albalate and Bel, 2012). This reduction in travel time plays a crucial role in garnering political and public support for the establishment of the HSR. This sentiment is supported by a survey conducted by Cascetta et al. (2011), which revealed that a substantial 71.2% of HSR passengers on the Rome-Naples route in Italy (covering 222 km) prefer HSR primarily due to the compelling factor of travel time reduction. This survey result underlines the fundamental and widespread public need for faster and more efficient transportation options.

The central goal of HSR investment extends beyond time savings, encompassing a vital focus on increasing capacity (de Rus and Nombela, 2007). This capacity enhancement is achieved through the provision of additional capacity by HSR itself and the subsequent release of capacity on existing routes. This strategic approach is particularly relevant for early HSR lines in some countries, where alleviating congestion on existing railways is a primary motivation. For instance, the pioneering HSR lines in Japan, such as the Tokyo-Osaka corridor (515 km) constructed in 1964, and France, like the Paris-Lyon corridor (425 km) established in 1981, were driven by the imperative to address capacity constraints. Both corridors have emerged as some of the world's most densely used passenger routes, underscoring the success of their capacity-focused approach. Moreover, German's first two HSR lines, connecting Hannover to Würzburg (327 km) and Mannheim to Stuttgart (109 km) in 1991 were conceived with a primary objective: to address congestion challenges on the existing railway network (Albalate and Bel, 2012).

Beyond these, numerous additional motivations underpin HSR investments. These include the potential for mode shift from air and road transport, resulting in reduced congestion on roads, decreased greenhouse gas emissions, improved air quality, and induced ridership on local transit systems (Albalate and Bel, 2012; Givoni and Banister, 2012). Additionally, HSR investments are known to enhance economic activity in regions (Chen and Hall, 2012; Preston and Wall, 2008) and therefore increase land and property value around HSR station (Huang and Du, 2021).

According to Bruun (2014), investments made in public transportation can lead to an enhancement in travel conditions, benefiting not only its direct users but also those who prefer alternative modes of transportation. This becomes particularly evident when a substantial increase in capacity is introduced along a heavily congested travel route. An illustration of this can be found in the case of the Korean government's decision in 2004 to establish their first HSR line connecting Seoul and Busan, covering a distance of 412 kilometers. This strategic move was a response not only to the congestion issues on the existing railway network but also to the challenges posed by traffic congestion on the highway that connects these densely populated urban centre (Kim and Sultana, 2015).

The introduction of High-Speed Rail systems, often resulting in reduced rail journey times, holds the potential to reshape passenger travel behavior. This, in turn, is expected to gain market shares from both air transport and private vehicle use, leading to a dual benefit of alleviating traffic congestion on roads and reducing environmental pollution (Haas, 2014).

To assess the influence of HSR from this perspective, various studies have focused on predicting mode shift- a phenomenon where passengers prefer alternative modes due to the introduction of HSR (Castillo-Manzano et al., 2015; Chen, 2017; Dobruszkes and Givoni, 2013; Jiménez and Betancor, 2012; Sun et al., 2017; Wan et al., 2016). Moreover, to generalise the scope of HSR's influence on mode shift, some researchers have defined specific distance and travel time ranges within which HSR can effectively compete against alternative modes. For example, within the speed range of 200–350 kph, HSR emerges as a preferred choice in China for intercity travel, encompassing distances between 250 km and 900 km, thereby challenging air and road transportation (Diao et al., 2017). On a temporal scale, HSR's competitive travel time tends to hover around 2 hours for road travel and 2.5-3 hours for air travel (Ureña et al., 2009).

However, uncommon examples can be seen in practice. Consider the instances of the Wuhan-Guangzhou (1039 km) and Beijing-Shanghai (1318 km) corridors, initially perceived as too extensive to effectively compete with air travel. Surprisingly, the opening of HSR lines along these routes led to a reduction of approximately 45% and 34% in air travel, respectively (Chen, 2017). A comprehensive overview of general mode shares for intercity travel spanning the range of 100–2000 km, with an average HSR speed of 300 km/h, is illustrated in Figure 1.2 by Fröidh (2014).

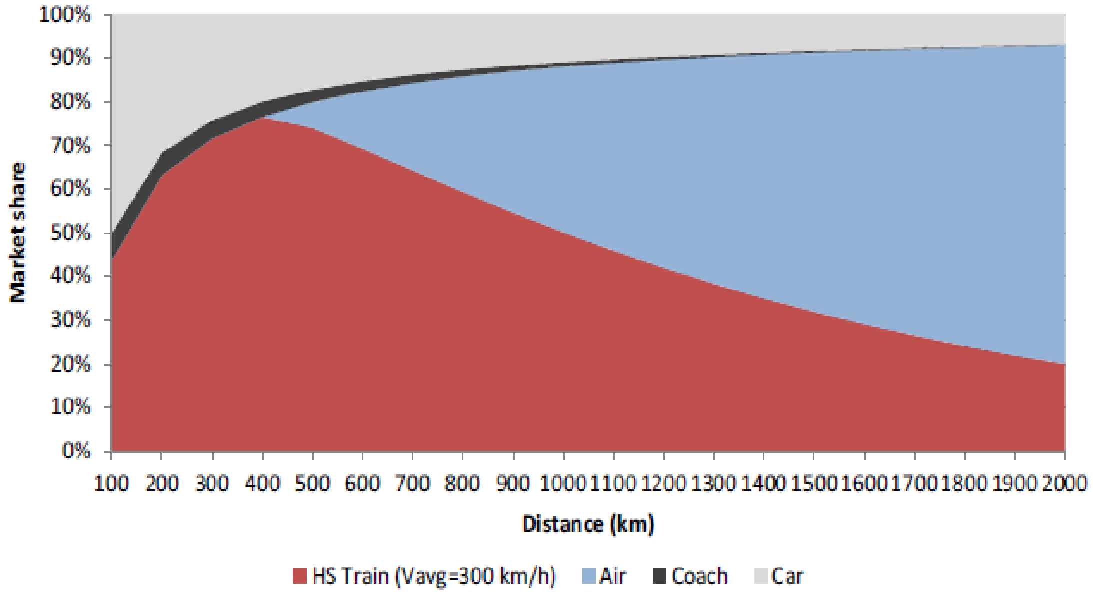


Figure 1.2 Generalised mode share for intercity travel

*Source:* (Fröidh, 2014, p.63)

Furthermore, a key aim of HSR implementation is the reduction of environmental pollution, encompassing factors like greenhouse gas emissions, air pollutants, and noise. It is claimed that high-speed train employed for intercity passenger transport are inherently more ecologically friendly than their counterparts, including aeroplanes (Givoni et al., 2009; Prussi and Lonza, 2018) and automobiles (Álvarez, 2010; Chester and Horvath, 2012).

To evaluate the environmental influence of HSR investment, a range of evaluation methodologies and parameters are employed, covering aspects such as energy consumption per seat-kilometer, carbon emission levels, electricity sourcing, vehicle occupancy rates, the proportion of demand attributed to mode shift, and the volume of newly generated demand (Westin and Kågeson, 2012). For example, Givoni et al. (2009) conducted a comparison of carbon emission intensity between HSR and air transport on the London- Paris corridor, concluding that HSR exhibits lower emission levels than air travel. Conversely, an investigation into the Turkish HSR system indicated that the shift from road transport to HSR did not result in significant emission reduction due to primarily attracting coach users to HSR (Dalkic et al., 2017). It's possible that the lower emissions per passenger of coaches compared to High-Speed trains and the unexpected stability in car usage have contributed to the sustained low emission reduction levels. This outcome likely stems from coaches having lower emissions per passenger, and the expected change in car usage not materialising as initially predicted.

The introduction of an additional intercity public transport mode (e.g. HSR) is strategically aimed at augmenting regional accessibility and connectivity. Multiple studies have explored the accessibility impacts of planned or established HSR projects at various scales, ranging from international to national, regional, and urban contexts (Cao et al., 2013; Gutiérrez, 2001; Gutiérrez et al., 1996; Jiao et al., 2014; Kim and Sultana, 2015; Martínez Sanchez-Mateos and Givoni, 2012; Wang et al., 2016; Yu and Fan, 2018). These studies collectively reveal that the level of accessibility enhancement exhibits substantial spatial variability, signifying that improvements tend to diminish as the distance from the station increases.

The notion that high-speed rail can act as a catalyst for economic transformation by bringing cities and regions closer together is a common assertion. Nevertheless, there is a lack of comprehensive research exploring the broader economic advantages of intercity rail systems. In attempts to asses the wider economic consequences of such investments, Preston and Wall (2008) noted that these encompass gains in productivity and efficiency resulting from reduced travel time and enhanced connectivity between the labour force and business establishments. Consequently, researchers seek to capture the expansive economic benefits stemming from shifts in accessibility dynamics (Chen and Hall, 2012; Jiao et al., 2020).

Finally, the introduction of HSR has potential to stimulate real estate markets and lead to rise in land and property values. However, comprehensive reviews conducted by Hensher et al. (2012) and Srivastava et al. (2023) revealed that there is a heterogeneous effect on land value with the introduction of HSR. While certain locations, such as London in the UK, and Ciudad Real in Spian exhibit a positive correlation between HSR projects and escalating land and property values, case studies centered around Paris in France and Rome and Milan in Italy illustrate a contrasting negative impact. The heterogeneous impacts shown for HSR appear to be linked to the highly variable outcomes observed in urban transport systems within cities (Hensher et al., 2012; Srivastava et al., 2023). Furthermore, Huang and Du (2021) estimates the impact of HSR on the land value in China by employing a difference-in-difference approach. Their research suggests that land values are higher during the HSR construction period compared to the operational period. This implies that positive public perceptions or expectations regarding HSR connections significantly contribute to driving up land prices in HSR cities after the commencement of HSR construction (Huang and Du, 2021).

The outlined planning aims for HSR projects prompt an exploration of potential hierarchical relationships among them, suggesting that the accomplishment of each goal is often interconnected with the attainment of others. It appears plausible to conceptualise a hierarchical structure such that (i) increasing speed to reduce journey time, (ii) the enhancement of network capacity and (iii) improving the service frequency are the first elements of this hierarchy. These components, as highlighted by Preston (2016), embody direct impacts of HSR, as shown in Figure 1.3. Consequently, the success of these initial facets may lay the groundwork for the success of subsequent ones. Moreover, within this primary level of aims, only journey time reduction is a particular feature for HSR system, distinguishing it from conventional trains. Thus, it is possible to conclude that achieving a significant reduction in travel time is an important step to justify investment in high-speed rail infrastructure.

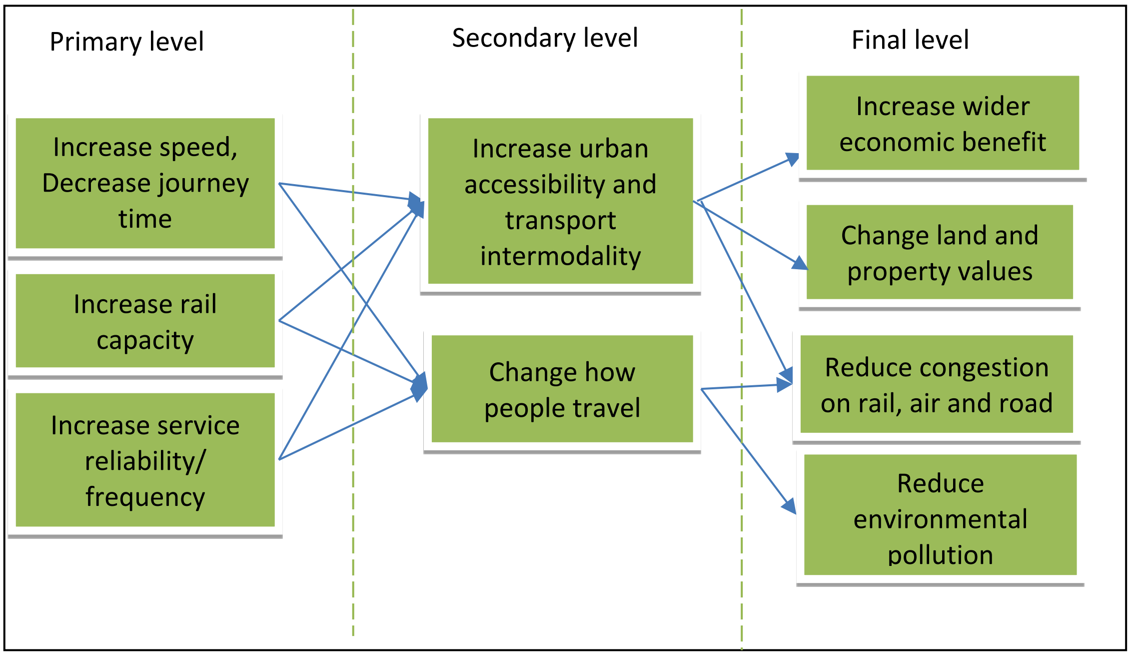


Figure 1.3 Hierarchical relationship between motivations

## 1.3 Problem statement

The literature surrounding High-Speed Rail systems has extensively investigated various dimensions of this subject. Particularly, HSR systems have been analysed within the realm of transport geography with a focus on the enhanced accessibility they bring to cities within the network. The existing literature on the subject evaluates enhancements in accessibility through diverse indicators, see Section 2.3, with travel time as the primary metric of impedance. These evaluations have been based on the approach of spatial shrinkage provided by HSR systems, which corresponds to the decrease in travel time (Spiekermann and Wegener, 1994). This approach is highly useful for assessing the changes in accessibility resulting from the introduction of new HSR infrastructure within the cities.

However, many existing studies tend to assess accessibility changes by exclusively focusing on the travel duration between stations. They assume that HSR systems affect accessibility beyond the immediate vicinity of stations, but do not actually quantify or test this. This assumption might result in an overestimation of actual spatial impact of accessibility. The concept of accessibility refers to the interaction between land use patterns and the transportation network. In this context, considering door-to-door journey time becomes crucial. The door-to-door journey time encompasses the complete travel experience including station access, waiting times, transfers, and travel to the final destination. Transport planning should focus on accessibility with door-to-door journey time aspect to understand how transportation impacts spatial systems from a wider perspective.

In addition to this spatial perspective, the concept of accessibility is further examined at the local level. Some studies have examined the accessibility of railway stations and assessed how these stations are seamlessly integrated into broader urban transport systems (Moyano et al., 2018). Particularly, researchers have focused on the node-place model which is a conceptual framework for areas surrounding stations, notably considering the integration of land use and transport modalities (Caset et al., 2018; Kim et al., 2018).

Within the realm of High-Speed Rail accessibility investigations, reseachers have been notably limited in their investigation of the complex interaction between local and regional integration of HSR stations. Although the accessibility of HSR is influenced not just by station-to-station travel time, but also by the time it takes to access and depart from HSR stations, researchers have often overlooked this holistic perspective. Focusing exclusively on station-to-station travel times when assessing HSR benefits can potentially mislead the actual advantages of such systems, resulting in an incomplete understanding of the overall impact. This narrow approach might inadvertently promote the placement of stations in locations that fail to maximise the time-saving potential of the new rail line. Therefore, this study focuses on the door-to-door journey time approach to evaluate the potential accessibility impact of HSR system. It specifically examines the role of public transport modes as an access mode to HSR stations.

## 1.4 Research aims and objectives

The overall aim of this thesis is to better evaluate the change in accessibility benefit across a region resulting from different scenarios of high-speed rail development, employing a door-to-door journey time approach. The aim will be achieved by meeting the following objectives:

1. Examine the factors that influence the accessibility benefits provided by High speed railways in interconnected cities. This is covered in Chapter 2.5.
2. Explore tools to compute door-to-door journey time calculations for public transport modes. This is covered in Chapter 3.7.
3. Investigate different methods for defining and segmenting the door-to-door journey time, which could be transferable to apply for any HSR corridor. This is covered in Chapter 4.
4. Assess the relative importance of different components of door-to-door journey time for intercity rail travel. This is covered in Chapter 4.
5. Empirically evaluate the implications of the station location for inter-city accessibility to better understand the necessary trade-off between inter-city accessibility and intra city accessibility. This is covered in Chapter 5.
6. Empirically assess the influence of station integration levels on the overall accessibility of high-speed rail systems. This is covered in Chapter 6.

## 1.5 Significance of the study

Existing studies commonly evaluate changes in accessibility by concentrating solely on the travel duration between stations. While these studies assume that HSR systems influence accessibility beyond the immediate station vicinity, they fail to quantify this assumption. Relying solely on travel duration may lead to an overestimation of the actual spatial impact on accessibility. Door-to-door journey time, which accounts for the entire travel experience, including station access, waiting times, transfers, and travel to the final destination, offers a more comprehensive perspective. Although some studies consider door-to-door journey time, their methodologies tend to be simplified, not fully capturing the complexity of the overall journey time approach. Additionally, existing studies that place door-to-door journey time tend to focus more on car usage for station access/egress rather than public transport modes.

Given the limited literature addressing intercity accessibility studies based on door-to-door travel time, this thesis applies a door-to-door travel time approach that simultaneously integrates both the inter- and intra-city part of a trip. Therefore, it provides a more precise and comprehensive accessibility analysis of intercity travel through high-speed rail. Notably, the inclusion of the intra-city phase, relying on public transport modes, adds a novel dimension to the door-to-door approach, further emphasising the uniqueness of this study.

Moreover, previous studies have predominantly focused on evaluating accessibility within historical or existing contexts, rather than quantifying the prospective implications of a future High-Speed Rail network on accessibility. By adopting a comprehensive door-to-door travel time approach, the rearch aims to evaluate the HSR planning scenarios overall to optimise its design to achieve the maximum accessibility benefits. Appropriate design choices are crucial for success. Focusing only on the centre-to-centre element of journeys is unlikely to deliver optimal outputs. Planning needs to extend beyond rail to incorporate land use and alternative transport modes. This thesis aims to inform decision-makers on high-speed railway system design and management and also on broader transport and urban planning.

Consequently, this study makes a substantial contribution by first highlighting the significance of door-to-door journey times when estimating accessibility using public transport. Subsequently, it demonstrates the profound impact that the strategic choice of high-speed rail station locations can have on the accessibility advantages offered by such rail systems to specific cities.

## 1.6 Thesis Outline

The thesis is structured across seven chapters, summarised in Figure 1.4. Following the introductory chapter, Chapter 2 includes a comprehensive understanding of high-speed railways, presenting a literature review that investigates the accessibility aspects of these systems. This chapter also undertakes an examination of the factors that wield an influence on the accessibility benefits derived from high-speed rail systems. Transitioning to Chapter 3, the methodology adopted for this study is introduced. It outlines the planned approach centred around door-to-door journey time assessment and explores alternative tools for journey time calculation before specifying the chosen tool for this research. Chapter 4 investigates the methodologies for calculating door-to-door journey time. It offers a comparison of their pros and cons while aligning with the thesis requirements. Additionally, this chapter highlights the relative significance of different journey time components. In Chapter 5, an empirical evaluation is conducted to examine the effects of station location on inter-city accessibility. Subsequently, Chapter 6 engages in an empirical assessment of how station integration levels impact the overall accessibility of high-speed rail systems. Lastly, Chapter 7 provides a concise summary of the thesis outcomes. It also addresses the study's limitations and reveals potential areas for future research.

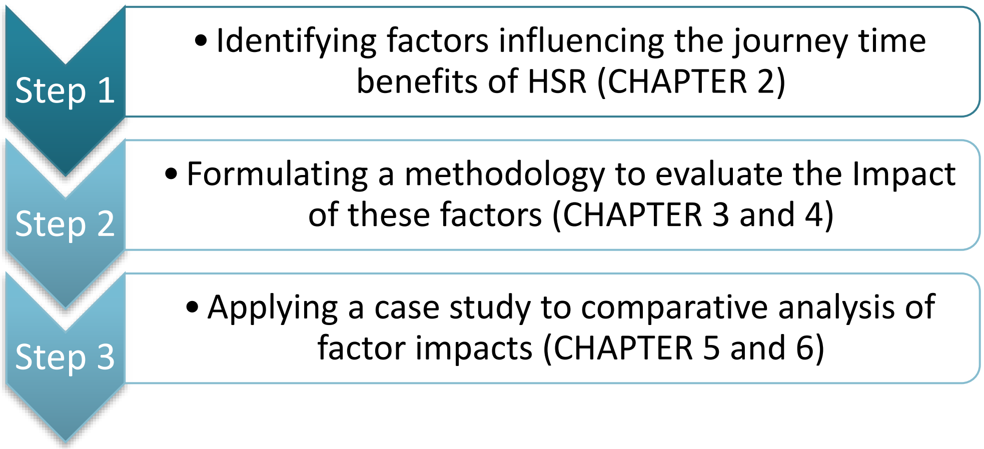


Figure 1.4 Diagram summarising the steps of the research

# Chapter 2 LITERATURE REVIEW

## 2.1 Introduction

This chapter involves a comprehensive exploration of High-Speed Rail accessibility within the context of existing literature. It commences by establishing a clear definition of HSR as outlined in relevant sources. Subsequently, the definition of accessibility, its measurement, and associated methodologies are examined. Furthermore, this segment aims to present an overview of prior studies that have investigated HSR accessibility, and highlight the existing body of knowledge in this domain.

To conduct this literature review, a comprehensive search encompassed academic journals, conference papers, doctoral theses, books, and government reports. The search employed a set of keywords in conjunction with "HSR": accessibility, interconnectivity, connectivity, multi-modality, co-modality, intermodality, door-to-door journey, total travel time, end-to-end journey, integrated transport modes, seamless journey, and inter-city journey. Academic databases including Scopus, Web of Science, CORDIS, and Google Scholar were queried to retrieve relevant publications. The screening process involved assessing the search results based on their publication date, with a focus on reading titles and abstracts. This critical evaluation was conducted to determine the relevance and appropriateness of each potential study for inclusion in the literature review.

Moreover, an investigation of the factors that influence the accessibility of HSR systems will be undertaken. Through this review, this section attempts to provide a comprehensive foundation for the subsequent exploration of HSR accessibility and its underlying dynamics.

## 2.2 High speed railway definition and generic route options

In literature, although an overall consensus on a universal definition has not been reached so far, the European Commission (1996) provides a definition of high-speed rail (HSR) to distinguish it from conventional railways. This definition is based on design speed and infrastructure. Systems that either have dedicated new tracks enabling speeds of at least 250 kilometres per hour (kph) or support speeds of over 200 kph on upgraded existing tracks are classified as high-speed railways. In theory, this technical definition outlines the design criteria of a high-speed rail system. However, there are also other definitions that reflect the operational aspects of HSR systems in practice.

Campos and de Rus (2009) defines four types of generic HSR route options, as shown in Figure 2.1 Model 1 (Exclusive exploitation) involves segregated tracks for both high speed and conventional trains, which in practice is often related to differences in track gauge between two systems. For example, conventional tracks were built with narrow gauge in Japan and broad gauge in Spain, whereas their high-speed lines are standard gauge. Japanese Shinkansen lines operated under Model 1 from 1964 to 1992, but after that, the narrow gauge of some conventional networks was changed to be compatible with high-speed trains.

In Model 2 (mixed high-speed), high-speed trains (HSTs) are mostly operated on dedicated new tracks, but some runs on conventional tracks to access destinations beyond the HSR network. The French TGV (Train à Grande Vitesse) service, operational since 1981, is a good example of this model. Additionally, international HSTs in the Netherlands run through conventional tracks to reach central stations. Model 3 (mixed conventional) allows conventional trains to run on high-speed tracks. Campos and de Rus (2009) provide an example of the Spanish case for this model, but plenty of high-speed trains operate on conventional tracks via gauge changers, making Spain an example of Model 2, or perhaps Model 4. Model 4 (fully mixed) is the most flexible model, allowing interchange between conventional and high-speed services. The German intercity trains (ICE) since 1988 and the Rome–Florence line in Italy are practical examples of this model.

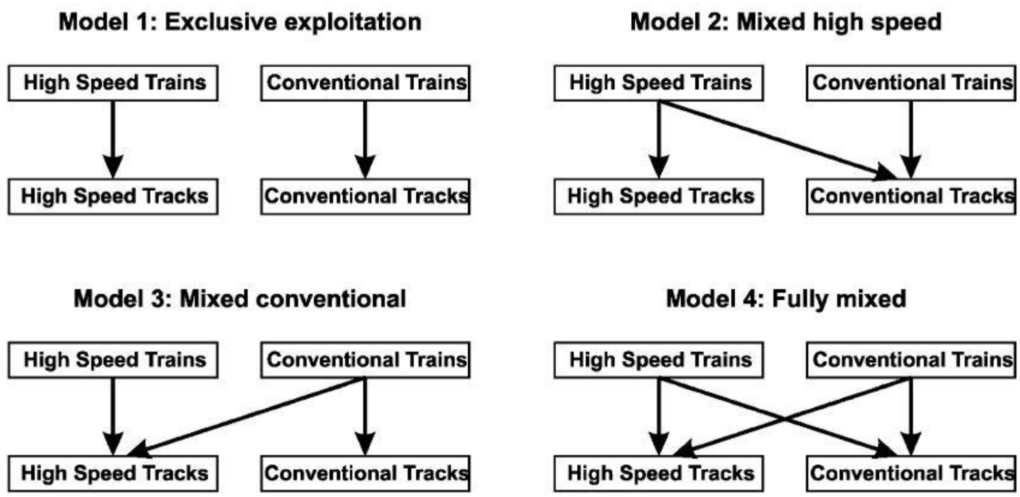


Figure 2.1 Type of HSR models

*Source:* (*Campos* and de Rus, 2009, p.21)

In addition to the criteria used for categorisation above, Preston (2016) suggested the addition of two criteria: station location and the constructional properties of a railway route. The former factor could be characterised by stations located in the city centre (e.g., London St Pancras, Gare du Lyons, and Paris Gare du Nord), at the edge of the city centre (e.g., Euralille, Lyon Part-Dieu, Shin Osaka), or at the edge of the city itself (such as the stations in China and Chinese Taipei). The latter can be characterized according to the percentage of the railway route composed of bridges, grade separations, and tunnels. Such a definition might also allow the comparison of construction costs of high-speed rail systems. In China, the dominance of such structures along an entirely segregated route leads to higher costs, whereas the mixed services help to reduce costs.

The International Union of Railways (UIC) is an international organisation that brings together railway operators and stakeholders from around the world. Its aim is to promote and coordinate international cooperation among railway companies and to contribute to the development and improvement of rail transport on a global scale. Table 2.1 shows the existing and planned HSR lines across the World in 2021. HSR is currently in operation in more than 20 countries (including China, Japan, South Korea, France, Germany, Belgium, Spain, Italy, Turkey, the UK, Saudi Arabia and Taiwan). HSR is under construction in more than 18 countries (including Iran, Spain, and the UK); and in development in another 17 countries (including Bahrain and Qatar, India, Iran, Kazakhstan, Vietnam, Czech Republic, Norway, Poland, Portugal, Russia, Sweden, Australia, Brazil, Canada, Egpyt, Mexico, Morocco, and South Africa).

Table 2.1 High-Speed Lines in the World

*Source:* (UIC, 2022a)

| Area | Country/ Region | Length(km) | | | | |
|---|---|---|---|---|---|---|
| | | 1. In operation | 2. Under construction | 3. Planned | 4. Long-term planning | Total |
| AFRICA | Egypt | - | - | 1,570 | 1,805 | 3,375 |
| AFRICA | Morocco | 186 | - | 640 | - | 826 |
| AFRICA | South Africa | - | - | - | 2,390 | 2,390 |
| ASIA-PACIFIC | China | 40,474 | 13,063 | 4,104 | 7,134 | 64,775 |
| ASIA-PACIFIC | India | - | 508 | - | 7,479 | 7,987 |
| ASIA-PACIFIC | Indonesia | - | 142 | 570 | - | 712 |
| ASIA-PACIFIC | Japan | 3,081 | 402 | 194 | - | 3,677 |
| ASIA-PACIFIC | South Korea | 873 | 49 | - | - | 922 |
| ASIA-PACIFIC | Thailand | - | 253 | 431 | 1,958 | 2,642 |
| ASIA-PACIFIC | Vietnam | - | - | 1,545 | - | 1,545 |
| ASIA-PACIFIC | Australia | - | - | - | 1,749 | 1,749 |
| EUROPE | Austria | 254 | 281 | 71 | - | 606 |
| EUROPE | Belgium | 209 | - | - | - | 209 |
| EUROPE | Czech Republic | - | - | 832 | 173 | 1,005 |
| EUROPE | Denmark | 56 | - | - | - | 56 |
| EUROPE | Estonia, Latvia, Lithuania | - | - | 870 | - | 870 |
| EUROPE | Finland | 1,120 | - | 394 | - | 1,514 |
| EUROPE | France | 2,735 | - | - | 1,725 | 4,460 |
| EUROPE | Germany | 1,571 | 147 | 81 | 210 | 2,009 |
| EUROPE | Hungary | - | - | 166 | - | 166 |
| EUROPE | Italy | 921 | 327 | - | - | 1,248 |
| EUROPE | Norway | - | - | - | 333 | 333 |
| EUROPE | Poland | 224 | - | 805 | 875 | 1,904 |
| EUROPE | Portugal | - | 80 | 418 | - | 498 |
| EUROPE | Russia | - | 659 | 421 | - | 1,080 |
| EUROPE | Serbia | - | 75 | 313 | - | 388 |
| EUROPE | Spain | 3,661 | 1,055 | 863 | - | 5,579 |
| EUROPE | Sweden | 860 | 214 | 338 | - | 1,412 |

| | | | | | | |
|---|---|---|---|---|---|---|
| EUROPE | Switzerland | 176 | - | - | - | 176 |
| EUROPE | Netherlands | 90 | - | - | - | 90 |
| EUROPE | United Kingdom | 113 | 225 | 341 | - | 679 |
| LATIN AMERICA | Brazil | - | - | - | 511 | 511 |
| LATIN AMERICA | Chile | - | - | - | 127 | 127 |
| MIDDLE EAST | BAHRAIN And QATAR | - | - | - | 180 | 180 |
| MIDDLE EAST | Iran | - | 410 | 1,043 | 1,651 | 3,104 |
| MIDDLE EAST | Israel | - | - | 85 | - | 85 |
| MIDDLE EAST | Saudi Arabia | 449 | - | - | - | 449 |
| MIDDLE EAST | Turkey | 1,052 | 1,596 | 2,011 | - | 4,659 |
| NORTH AMERICA | Canada | - | - | - | 1,523 | 1,523 |
| NORTH AMERICA | Mexico | - | - | 210 | - | 210 |
| NORTH AMERICA | USA | 735 | 274 | 1,278 | 3,784 | 6,071 |
| Africa (3) | | 186 | 0 | 2,210 | 4,195 | 6,591 |
| Asia Pacific (8) | | 44,428 | 14,416 | 6,844 | 18,320 | 84,008 |
| Europe (20) | | 11,990 | 3,062 | 5,913 | 3,316 | 24,281 |
| Latin America (2) | | 0 | 0 | 0 | 638 | 638 |
| Middle East (5) | | 1,501 | 2,006 | 3,139 | 1,831 | 8,477 |
| North America (3) | | 735 | 274 | 1,488 | 5,307 | 7,804 |
| Total (42) | | 58,839 | 19,759 | 19,594 | 33,607 | 131,799 |

*Lines or sections of lines in which operation V ≧ 250 km/h*
*In operation is now operating on High Speed, under construction is now constructing of High-Speed lines, planned is approved but not start constructing, long-term planning is not approved, just planned.*

## 2.3 Accessibility in transport studies

Accessibility represents a crucial analytical concept for the evaluation of transportation networks. In the realm of transportation, it has attracted considerable interest due to its relevance in understanding spatial interactions, which can be explored through diverse methods and conceptual frameworks. Typically, accessibility is defined as “potential of opportunities for interaction” (as defined by Hansen, 1959). This definition reflects the idea of evaluating the ease of specific movements occurring under different conditions.

This concept finds broad application in transport planning, urban planning, and geography. Transport accessibility measures aim to quantify the overall benefit that residents of a specific geographic region can receive from the proximity or ease of travel to opportunities located elsewhere (Geurs and van Wee, 2004; Gutiérrez et al., 1996). Thus, these measures assist policymakers in making informed and evidence-based decisions. This indicator can be applied to both ex-post assessment of existing transport supply, and also ex-ante studies to identify the expected outcome of new infrastructures or services and maybe to identify the best practices and provide policy recommendations. To find out more, the Transport Access Manual by David Levinson is a comprehensive guide for quantifying and evaluating access in transportation and land use planning.  The manual likely provides insights and methodologies in transportation and urban planning to gain a deeper understanding of the accessibility within city or region (Levinson, 2020).

Transport geography, along with other research fields, has extensively examined accessibility from various angles. This includes defining the concept, translating these definitions into practical indicators, deliberating on the advantages and drawbacks of these indicators, devising methods to compute these indicators, and ultimately implementing them in real-world scenarios. In general terms, transport accessibility of a place *i* in relation to a place *j* is the outcome of two functions, one representing the “attractiveness” of the areas that can be reached and one representing the “effort of travel” needed to reach them. The functions g(Wj) and f(Cij) are called “activity function” and “impedance function”, respectively.

$$A_{ij} = g(W_j)\, f(C_{ij})$$

Where: $A_i$: accessibility of area i, $W_j$: attractiveness of area j, Cij: the effort of travel between origin *i* and destination *j*

Based on this common concept of accessibility, different theoretical interpretations and measurement have been developed (Geurs and van Wee, 2004; Gutiérrez, 2001; Lei and Church, 2010; Liu and Zhu, 2004; Rietveld and Bruinsma, 1998). In particular, Geurs and van Wee, (2004) summarise four types of accessibility measures: (1) infrastructure based, (2) location based, (3) person based and (4) utility based. First, infrastructure-based accessibility concentrates on aspects such as time, congestion, and operational speed within the transport network. Second, location-based accessibility measures consider how opportunities, such as services, resources, or activities, are distributed across different spatial areas. This entails understanding the geographical spread of these opportunities and the associated demand for them in different locations. Third, person-based measures focus on an individual's ability to engage in activities within a given timeframe, emphasising personal freedom to participate in activities considering time and transportation conditions. Finally, utility-based accessibility measure is assessed at the individual level, assuming that users seek to optimise the benefits of their travel while accounting for costs. This approach incorporates characteristics of both users and transportation modes.

Location-based accessibility measures are frequently used in literature due to their ease of assessment and communication, as well as their lower data demands. Researchers often find them suitable for informing and observing the achievement of transport planning goals (Páez et al., 2012). Moreover, the other measures have some limitations: infrastructure-based measures do not adequately address the analysing of the spatial distribution of opportunities, and utility-based and person-based accessibility measures present challenges due to their high data requirements and complex interpretation processes.

Three location-based indicators stand out as frequently used in the literature: daily accessibility, potential accessibility, and weighted average travel time. These indicators capture the essence of accessibility measurements, which consist of two core components: "attractiveness" and "travel effort." This enables the expression of accessibility measures either in terms of the units of attractiveness or in terms of the units of transportation impedance.

Transport impedance is commonly quantified using travel distance or travel time (Shaw et al., 2014). However, employing a time-based measure is more practical, as a distance-based metric may not adequately capture variations in speed (Rietveld and Bruinsma, 1998). To provide a more comprehensive representation of travel behaviour, a Generalised Transport Cost (GTC) function is often integrated as the travel effort. This GTC function encompasses a set of impedance factors, typically expressed in terms of monetary cost and time cost (Koopmans et al., 2013; La Paix Puello and Geurs, 2016). The attractiveness of destinations is frequently measured by indicators such as employment figures, population size, or Gross Domestic Product (GDP). In certain instances, the attractiveness value (Wj) can be a combined mass factor, such as the square root of a combination of population and GDP factors for the destination (Jiang et al., 2023; Jiao et al., 2014; Yu and Fan, 2018), as illustrated below for clarity:

$$W_j = \sqrt{Population \times GDP}$$

### 2.3.1 Daily accessibility (DA)

This is also known as a contour measure, iso-chronic indicators, cumulative opportunities, or proximity count. This indicator estimates the availability of opportunities within a predefined distance/time-threshold or within certain travel cost limits. The time limit is usually set to 3 or 4 hours so that it is possible to go and return within the day.

The primary drawback of the measures is that they assess accessibility in relation to the transit system itself, rather than focusing on the accessibility between origin and destinations. To address this limitation, a common approach involves combining daily accessibility measures with weighted average travel time measures (Kaplan et al., 2014).

$$DA_i = \sum_{j=1}^{n} W_j$$

where DAi is the daily accessibility of location i; $W_j$ is attractiveness of destination, j; n is the number of destinations.

### 2.3.2 Potential accessibility (PA)

This is also known as economic potential accessibility, gravity or opportunity approach, potential value or a gravity-type indicator. These measures also consider the impedance between origins and destinations.

$$PA_i = \sum_{\mathbf{i=1}}^{\mathbf{n}} \left( \frac{\mathbf{W_j}}{\boldsymbol{C}_{\mathbf{ij}}^{\mathbf{a}}} \right)$$

where $P_i$ represents the potential accessibility (PA) of location i; $C_{ij}$ is the effort of travel between origin *i* and destination *j*; $W_j$: attractiveness of area j; n is the number of destinations; the parameter a is a gravity parameter usually assumed to be equal to 1 (Gutiérrez, 2001).

### 2.3.3 Weighted average travel time (WATT)

This indicator counts for the spatial distribution of opportunities available in j. It is suitable to compare accessibility across time, place and travel mode, calculating the travel effort between one location and all the other locations, then it is weighted by the attractiveness of the destinations.

$$\mathrm{WATT_i} = \frac{\sum_{\mathbf{j=1}}^{\mathbf{n}} (\mathbf{C_{ij}} . \mathbf{W_j})}{\sum_{\mathbf{j=1}}^{\mathbf{n}} (\mathbf{W_j})}$$

Where $WATT_i$ is weighted average travel time of location i; $C_{ij}$ is the effort of travel between origin *i* and destination j; $W_j$: attractiveness of area j; n is the number of destinations.

Notably, understanding how to interpret these numerical outcomes holds significance for policymakers. Both the Weighted average travel time (WATT) and Daily accessibility (DA) indicators offer results in tangible units (hours and population, respectively), making them easily understandable. However, the Potential accessibility (PA) value lacks a straightforward interpretational unit, making it potentially more challenging to interpret.

## 2.4 High speed rail accessibility

High-Speed Rail systems have been a subject of comprehensive analysis in the field of transport geography, primarily focusing on the substantial improvements in accessibility they bring to cities integrated into the network. Within the existing body of literature, the evaluation of these accessibility enhancements employs a range of diverse indicators, as outlined in Section 2.3. These evaluations predominantly adopt a spatial shrinkage perspective facilitated by HSR systems, a concept provided by Spiekermann and Wegener (1994). This approach is highly useful for assessing the changes in accessibility resulting from the introduction of new HSR infrastructure within the cities. Spiekermann and Wegener (1994) captures the evolution of time-space dynamics within the European rail network, contrasting the years 1993 and 2010. Figure 2.2 visually shows how faster transport modes change the relationship between space and time, even though it might appear somewhat overestimated. It's a nice visualisation to understand the impact more comprehensively.

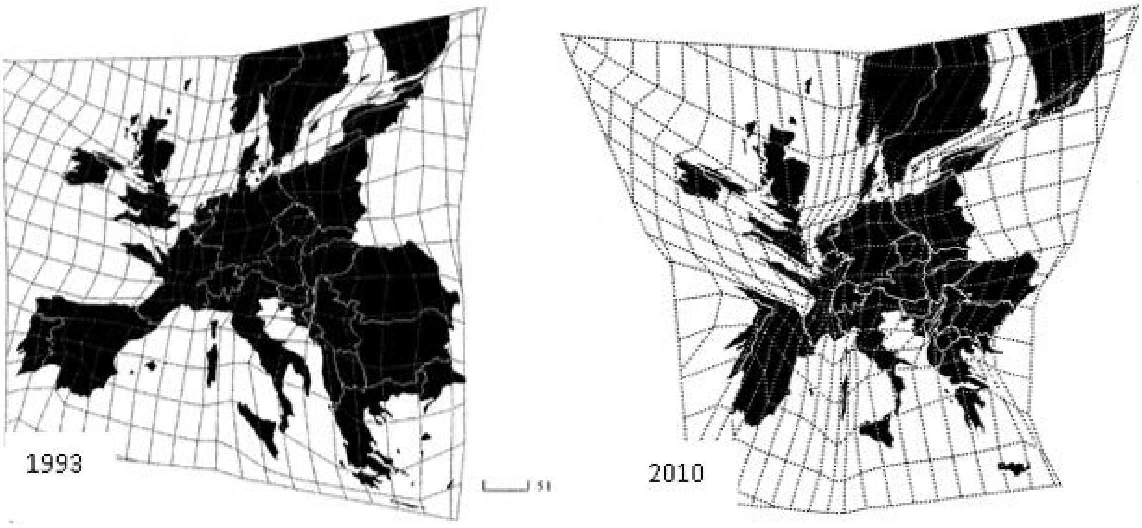


Figure 2.2 Time-space maps of the rail network in Europe

Source: (Spiekermann and Wegener, 1994)

Many research studies have integrated the concept of accessibility to explore the implementation of High-Speed Rail and its consequential spatial effects. In some research studies, when evaluating HSR accessibility, a common approach involves comparing the impact of the high-speed rail network with conventional trains, airline routes and private car travel. For example, Cao et al. (2013) conducted an analysis wherein they estimated and compared alterations in the accessibility of Chinese cities under different HSR, conventional rail, and airline availability scenarios. Their findings highlight that the air network remains very important in a country where long distances are common, HSR can only compete with the airline for the mid and short distance travel.

Existing HSR accessibility studies can be broadly categorised into two main groups. The initial category predominantly centres on intercity accessibility. Within this study group, cities are represented as single nodes, which may oversimplify the spatial interactions between a city and transport system. Gutiérrez et al. (1996) examined how a future high-speed rail network might impact the accessibility of European cities. They used weighted average travel time indicators and potential accessibility indicators and found that HSR could make the greatest contribution to the accessibility of cities in EU countries. Gutiérrez (2001) predicts the accessibility impact of the high-speed Madrid–Barcelona–French border train corridor on the 88 cities (13 of them in Spain) within the European Union border at different geographical scale, international and national (Spain).

Moreover, Martínez Sanchez-Mateos and Givoni (2012) examined the accessibility impact of the HS2 corridor at the regional level, measuring travel time saving from the 105 points conventional train stations in the UK to London. The accessibility indicator only includes the travel time and excludes the attractiveness of destination cities. In other words, it ignores the interaction between cities. The findings shows that the accessibility benefits of a proposed HSR line are likely to be limited to the main cities having an HSR station and will not spread through nearby cities and regions which are outside the HSR network.

Additionally, Jiao et al. (2014) assessed the accessibility impact of the future Chinese HSR network in 2020 in 337 cities (whole of China), but only 111 cities have HSR stations in their municipal district. Kim and Sultana (2015) evaluated the accessibility impact of the extension of Korean High-Speed Rail network and found that the HSR extension improves the accessibility level of isolated regions in South Korea. Wang et al. (2016) used daily accessibility indicator and created isochrone maps, which illustrate areas having similar travel time from Nanjing city (origin) to other cities (destination) in Jiangsu province, to evaluate the effect of a planned 20 HSR lines in 2030 on journey time. Findings show that there would be substantive time savings from Nanjing to peripheral cities, whereas the change is little from Nanjing to nearby cities.

Weng et al. (2020) assesses China's HSR network's impact on tourists' transportation choices and destination accessibility across 336 prefecture-level municipalities. Their study evaluates how HSR, along with aviation and expressways, affects accessibility. Findings reveal a 12.8% increase in the market potential of all Chinese cities due to HSR, with notable enhancements seen in small- and medium-sized cities. Cascetta et al. (2020) examined the impacts of Italy's high-speed rail system after a decade of operation. The study reveals significant improvements in transport accessibility (+32%) along the HSR network.

Cavallaro et al. (2022) conducted a comparative analysis of two HSR infrastructures, focusing on their impact on accessibility to key destinations: constructing a new segregated line versus upgrading an existing line. This study is applied to Venice–Trieste line in northeastern Italy, an area with medium-sized municipalities and existing transportation infrastructure. The findings suggest that upgrading the existing line is more beneficial for local commuters in terms of average travel times and social equity, while also being cost-effective compared to building a segregated HSR line.

Bruzzone et al. (2023) discuss the use of cost-benefit analysis (CBA) in assessing the impacts of high-speed rail and highlight the failure of CBA to address equity and accessibility issues in transport planning. They describe complementary methods to calculate the variation in equity and accessibility and then apply them to assess the equity and accessibility impacts for the Italian municipalities along the Turin-Lyon HSR. The study, therefore, emphasises the importance of integrating equity and accessibility considerations into transport project evaluations and decision-making processes.

The second category focuses on the intracity accessibility, or station-wide accessibility. These studies have examined the accessibility of railway stations and assessed how these stations are seamlessly integrated into broader urban transport systems. Researchers in this area analyse variables affecting local accessibility, such as distance or access time (Brons et al., 2009) and other variables related to station infrastructure and services (Reusser et al., 2008). Zhang et al. (2016) examined a station accessibility under four different scenarios which are related to improvement of HSR network, conventional rail network and road network. Moyano et al. (2018) performed a spatiotemporal accessibility analysis for HSR stations in Madrid and Barcelona. Their findings revealed significant variations in access and egress times throughout the day, influenced by factors such as traffic congestion and the frequency of public transport services.

Particularly, there are other researchers focused on the node-place model which is a conceptual framework for areas surrounding stations, notably considering the integration of land use and transport modalities (Caset et al., 2018; Kim et al., 2018; Wei and Wang, 2023). Moreover, Romero et al. (2021) conduct an assessment to determine if a peripheral station could complement the central station through the utilisation of a generalised cost function. In the case of Seville (Spain) the study revealed that a new peripheral station would only draw a limited portion of passengers (7.9% of individuals residing in the province) away from the existing central station.

However, HSR accessibility studies have often neglect the crucial connection between inter- and intracity segments of a trip. While assessing HSR accessibility, it's not only the station-to-station travel time that matters but also the time taken for accessing and leaving HSR stations. Monzón, Ortega and López (2016) emphasise that influence of the first and last mile can be a determinant in door-to-door HSR trips. Therefore, it's essential to assess HSR accessibility from a door-to-door travel perspective, which better reflects reality compared to a station-to-station time perspective (Wang et al., 2013, 2016; Yu and Fan, 2018).

Door-to-door travel time using public transport consists of two components: in-vehicle time (station-to-station) and out-of-vehicle time (access/egress and transfer time, waiting time, schedule delay). The station-to-station time depends on vehicle speed and the number of stations. Waiting time is linked to service frequency. Access/egress time is influenced by factors such as station location and the transport modes used for reaching the station. Transfer times can vary based on factors such as distance between platforms, station layout, efficiency, and coordination between trains, physical and spatial characteristics of the station and its surroundings. Moreover, there might be uncertainty in travel time resulting in schedule delay which is a difference between original timetable and rescheduled one. Although the presence of schedule delay impacts the accessibility provided by public transport system, the inclusion of this impact into accessibility measurement is very complex for multiple trip case.

While some studies address out-of-vehicle time components, their methodologies are often simplified. For example, transfer time between trains is sometimes represented as a transfer penalty, disregarding varying service frequencies at different stations (Monzón et al., 2013). Waiting time assumptions, such as it being half of the train headway time, overlook variations along routes during different times of the day (Wang et al., 2013). However, Wang et al. (2013) employed a comprehensive method for assessing access and egress times in their study. Their approach involves considering many districts within a city as potential origin points, enabling a more accurate representation of access and egress times for HSR users.

Moreover, the study conducted by Diao et al. (2017) and Jiang et al. (2023) incorporate access and egress times into their analysis by treating cities as singular entities, but they overlook the variations in accessibility within these cities by viewing them as single nodes. Zhao and Yu (2018) also introduced a door-to-door travel time framework to assess the modal competition within intercity travel. They specifically applied their approach to evaluate the feasibility of the proposed Dallas-Houston High-Speed Rail route. However, their study had a limitation in that it did not account for public transportation options when analysing access and egress modes. Likewise, Yu and Fan (2018) assessed the accessibility impact of future high speed rail corridor on the Piedmont Atlantic megaregion in the United States. Fan et al. (2022) reviews China's HSR network evolution, assesses accessibility improvements, and explores their impact on regional economic productivity. The study measure HSR network development over two periods, from 2007 to 2012 and from 2012 to 2018. Both studies adopted a door-to-door journey time perspective but limit their analysis to travel by car for access and egress segments.

In a study by Wang and Duan (2018) in the Yangtze River Delta, China, the concept of "loser" and "winner" cities was introduced with the operation of an HSR network. They stressed that having an HSR station in a city does not guarantee benefits; station location and accessibility to densely populated areas also play a vital role. Consequently, evaluating station impact requires a comprehensive approach, factoring in intra-city, inter-city, and potential transfer times. Their findings indicated that reduced inter-city rail travel times made intra-city travel more appealing for HSR users.

Existing studies vary based on the methods and data forms they use. Access computation relies on road network data that include spatial information and travel time for each link, facilitating routing algorithms to generate isochrones for various transport modes. Changes in network topology and travel time, such as new road construction or traffic signal adjustments, directly impact access results. Real-time travel speed data from GPS trackers and navigation systems provided by companies like TomTom, HERE technologies, and Uber Movement enhance the accuracy of accessibility tools (Levinson, 2020).

Datasets on public transport services are crucial for understanding mobility pattern. The General Transit Feed Specification (GTFS) standard is extensively employed for digitally representing public transport schedules and stop locations, establishing itself as the global standard for releasing public transit routes. Particularly for studies focusing on intra-city accessibility, this dataset holds paramount importance (Moyano et al., 2018). Real-time applications of GTFS further enhance transit analysis by providing insights into the actual operation and reliability of transit services beyond scheduled times.

In Geographic Information System (GIS) applications, two primary methods are commonly used to model travel time for journeys: cost distance analysis (Wang et al., 2016; Wang and Duan, 2018; Yu and Fan, 2018; Zhang et al., 2016) and network analysis (Jiang et al., 2023; Monzón et al., 2016; Yu and Fan, 2018). These methodologies are operated with raster dataset and vector dataset respectively. Cost distance analysis calculates the effort or cost required to travel from one location to another by assigning a cost value to each cell in a raster grid representing the study area. Different travel modes are processed separately by applying cost distance analysis in different layers. Each layer represents a specific travel mode, and cost values are assigned to cells based on the difficulty of traversing them using that particular mode. Once cost distance analysis is performed for each travel mode layer, the results are combined to create a composite raster that reflects the minimum cost of travel across all modes.

In addition to network performance, accessibility studies also incorporate the effect of the attractiveness of destinations. Most accessibility studies consider population or employment as proxies for destination attractiveness. Recently new data sources (Twitter) have also been used to reflect the attractiveness of destinations (Moyano et al., 2018). Population and employment data offer static measures of cities' activity, capturing population distribution at night or during the day, respectively, but not accounting for people's locations throughout the day or those who are at home during daytime hours. Table 2.2 summarises High-Speed Rail accessibility studies, highlighting the accessibility indicators utilised, study areas, geographical scales, and the consideration of door-to-door journey time in the analyses.

Table 2.2 HSR accessibility related studies

| **Study** | **Study area** | **Intra-city access** | **Geographical scale** | **Indicators*** |
|---|---|---|---|---|
| Gutiérrez, González and Gómez (1996) | Europe | Not available | International (European cities) | WATT, PA |
| Gutiérrez (2001) | Europe | Not available | International (European cities) | WATT, PA, DA |
| Martínez Sanchez-Mateos and Givoni (2012) | UK | Not available | Regional | Travel time |
| Cao *et al.* (2013) | China | Not available | National | WATT, PA, DA |
| Wang et al. (2013) | China | Multiple points (car access) | Regional | WATT |
| Monzón et al. (2013) | Spain | Multiple points (car access) | National | PA |
| Jiao *et al.* (2014) | China | Single point (car access) | National | WATT, PA, DA |
| Kim and Sultana (2015) | South Korea | Not available | National | WATT, PA |
| Wang et al. (2016) | China | Multiple points (car access) | Regional (Jiangsu province) | DA |
| Zhang et al. (2016) | China | Station accessibility | Regional | DA |
| Monzón et al. (2016) | Spain | Multiple points (car access) | Regional | PA |
| Diao et al. (2017) | China | D2D | National | WATT |
| Yu and Fan (2018) | USA | Multiple points (car access) | Regional | WATT, PA, DA |
| Zhao and Yu (2018) | USA | Multiple points (car access) | Dallas & Houston cities | Travel time |
| Wang and Duan (2018) | China | Multiple points (car access) | Regional (Yangtze River Delta) | Travel time |
| Moyano et al. (2018) | Spain | Station accessibility | Barcelona & Madrid cities | WATT |
| Weng et al. (2020) | China | Not available | National | PA |
| Cascetta et al. (2020) | Italy | Not available | National | PA |
| Romero et al. (2021) | Spain | station accessibility | Seville city | Travel time |
| Fan et al. (2022) | China | Multiple points (car access | National | DA and travel time |

| | | | | |
|---|---|---|---|---|
| Cavallaro et al. (2022) | Italy | Multiple points (car access) | Regional | WATT |
| Jiang et al. (2023) | China | Single point (car access) | National | DA and PA |
| Bruzzone et al. (2023) | Italy | Single point (car access) | Regional | PA |

**Weighted average travel time (WATT), Potential accessibility (PA), Daily accessibility (DA)*

## 2.5 Factors impacting accessibility of HSR system

This section summarises the thesis's understanding of the factors that affect door-to-door journey time made by HSR trains. The examination regarding to factors affecting journey time considers the entire transport chain (in cases where the primary leg is by rail) and the individual transport modes involved (i.e., air, rail, road, bus/coach and ferry). There can be a wide range of factors causing variations such as traffic accidents, changes in weather conditions, driving behaviours, the impact of pedestrian or bicycle movements on traffic, number of stop/station, route length, departure delay relative to the scheduled departure time, number of traffic signals, traffic congestion level, the time of day and the day of the week, even if the route is the same (Moyano et al., 2018).

Moreover, the consideration of journey time from the traveller's perspective entails more than just trying to reduce actual travel times, it also involves addressing the level of passenger satisfaction and needs. Many factors have a positive or negative impact on the overall passengers experience in various dimensions, such as schedules, temporal constraints, comfort, safety, and convenience (Brons and Rietveld, 2009a). While considering the HSR rail system main and its complementary components for door-to-door journey, the factors have been categorised in seven categories. The factors that have been identified encompass the following areas: (1) design characteristics of HSR corridors, (2) integration between transport networks, (3) infrastructure, service, and traffic management aspects, (4) the planning, design, and location of rail stations, (5) pricing and ticketing mechanisms, (6) travel planning and user information systems, as well as (7) considerations regarding traveller comfort, safety, and convenience.

### 2.5.1 Design characteristic of HSR corridor

The in-vehicle journey time represents the duration along the railway route and is affected by factors such as train speed, the number of intermediate stations and the distance between origin-destination stations. The number of stations along the route, as well as their placement, has a direct impact on the operational speed of the train. Speed reduction is technically related to processes like deceleration, acceleration, and the time allocated for passenger service during train dwell times (for loading and unloading). To ensure passenger comfort and safety, trains typically require a distance of 10–20 km to accelerate from 0 to 300 km/h. When a train is travelling at a speed of 300 km/h, the braking distance is approximately 5 km (Brunello, 2018). These factors collectively imply that each additional station can lead to an increase of around 5–10 minutes in travel time, although this value is subject to change based on the train's speed.

An illustrative trade-off curve was developed by the US Department of Transportation in 1990 (Figure 2.3) that correlates average line speeds with the average distance between stations. In an analysis of eight corridors with the same inter-station distance (103 km), it was observed that as the distance between stations grows, the average operational speed experiences a significant decline (as cited in Huang and Morgan, 2011; Brunello, 2018). Consequently, the presence of closely spaced intermediate stations along the route diminishes the journey time advantages of high-speed rail systems for major cities situated at the end of the line. While some argue that the reduction in benefits for major cities can be compensated by increased demand and enhanced accessibility for smaller locations, others indicate that this compensation might not be feasible for every corridor.

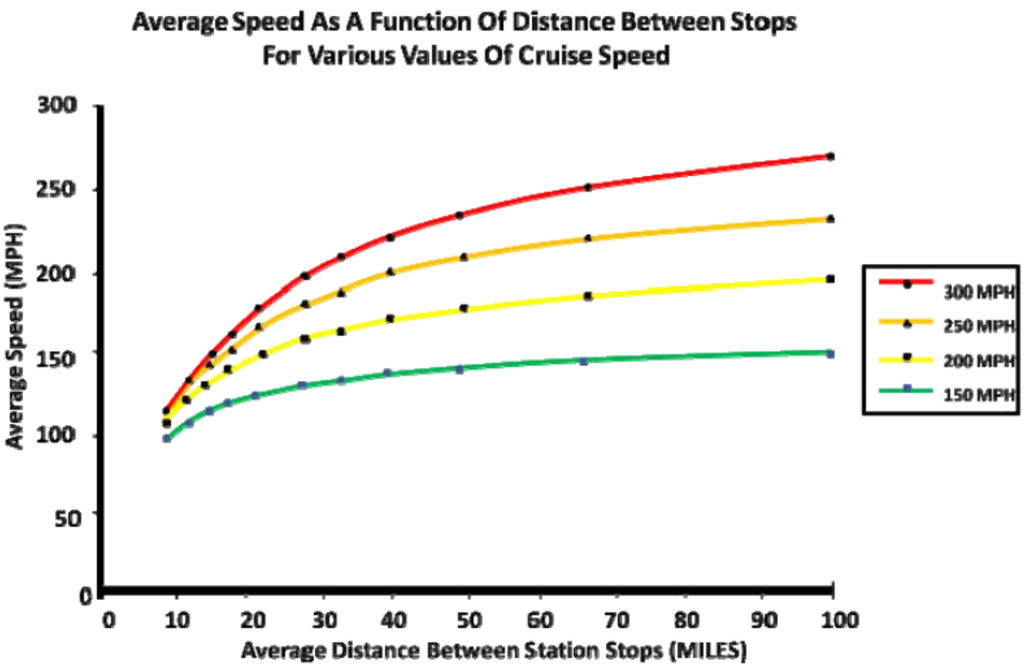


Figure 2.3 Average operational speed depending on the distance between stations

*Source: cited in Huang and Morgan (2011) and Brunello (2018)*

The High-Speed Rail lines typically have a smaller number of stations in comparison to conventional railways. Additionally, high-speed trains might not stop at all intermediate stations despite their presence along the route. For example, the Wuhan–Guangzhou HSR line in China, spanning 922 km, initially operated as a non-stop service, bypassing 13 intermediate stations along its course, which facilitated achieving the maximum operational speed of 312 kph (Brunello, 2018). However, this non-stop service was eventually discontinued due to insufficient passenger demand.

In the UK, the HS1 route that connects London to the Channel Tunnel features four stations along its 109 km length. The system serves central London via St Pancras International, East London through Stratford International, and Kent via Ebbsfleet International and Ashford International stations. The number of stations might appear relatively high for the given distance, leading to the majority of trains bypassing certain stations. For instance, Eurostar international trains do not make stops at Stratford International station and Ashford International station. Passengers using these stations must transfer to the backward (St Pancras) via domestic South-eastern trains and endure a wait of around 30 minutes at these stations to catch Eurostar international trains.

Marti-Henneberg (2015a) offers insight into the average inter-station distance for existing HSR lines in select EU countries, utilising data from the UIC website. This analysis reveals that Italy maintains one HSR station per 132 km of HSR track, while France has one every 119 km, and Spain features one every 84 km.

### 2.5.2 Integration between transport networks

Integration across various transport modes plays a crucial role in delivering a coherent and seamless door-to-door journey experience. Although high-speed rail infrastructure offers rapid travel, it is not seamless enough for passenger trip. Establishing a seamless and efficient connection between an HSR station and local transportation services can significantly enhance the passenger experience. Failing to achieve this connection can undermine the time savings achieved through high-speed travel between HSR cities by adding additional time needed to reach the ultimate destination. In such instances, the perceived benefits of HSR, stemming from its speed advantage, might become less substantial once the time required to access the HSR station and subsequent local transportation is factored in. Consequently, potential HSR passengers may lose their confidence in HSR, thereby diminishing its competitive advantage over other transportation alternatives (Mota et al., 2017).

The research conducted by Wong and Habib (2015) evaluates the impact of transit station accessibility on the preferences for intercity travel modes. The findings demonstrate that travellers prioritize the ease of reaching and leaving transit stations over the actual travel experience within the vehicle when making decisions about intercity travel modes. This implies that the success of travel options related to the provision of convenient access to and exit from stations.

Furthermore, fostering enhanced integration between long-distance journeys holds significant importance. In certain instances, establishing seamless interconnections can result in substantial time savings for passengers during transit. Martínez Sanchez-Mateos and Givoni (2012) observed changes in accessibility at conventional train stations following the introduction of a new High-Speed Rail line in the UK. Their study focused on evaluating the interconnections between conventional and high-speed routes, both of which cater to long-distance journeys. The study employed the travel time to London as a primary benchmark for assessing the accessibility of stations across both the conventional and high-speed rail networks. Hence, the study focuses on the potential winners and losers resulting from the establishment of a high-speed rail line. The analysis findings indicate that the advantages in terms of improved accessibility, stemming from the proposed line, are rather limited in their extent of spatial coverage. A considerable number of cities located near the new line would not encounter reduced travel durations for trips to London, resulting in the absence of any accessibility improvements in this aspect. The paper concludes by asserting that any assessment of a high-speed rail line must encompass a broader geographical scope beyond solely the cities and stations situated along the route. Additionally, the study emphasises the necessity of considering the integration between various transportation networks, particularly the seamless connection between the high-speed and conventional railway systems.

### 2.5.3 Infrastructure, service, and traffic management

Door-to-door travel time is influenced not only by the availability of infrastructure investment, but also by effective management of existing services. This management strategy relies on advancements in organising local transportation services, even without extensive investments in new infrastructure. By properly managing the transportation infrastructure, it becomes feasible to increase the capacity of existing facilities without substantial investment, leading to heightened average travel speeds—ultimately translating to reduced travel times. Furthermore, this approach enhances travel reliability and safety, consequently reducing the perceived time spent by users.

In certain scenarios, local transport services may exist, but they are insufficient to adequately meet the needs of connecting travellers. Common issues include poorly coordinated timetables, distant bus stops requiring extensive walks, and congested feeder roads to stations—each impacting waiting time, transfer time, and access time, respectively. To establish seamless transfers and minimise passenger wait times at stations, established methods in transport service management involve synchronising schedules between interconnected services and increasing the frequency of  train service (Niu et al., 2015).

Interestingly, there is a claim that improving service frequency holds greater benefits than reducing access/egress times to stations (Brons et al., 2009). This perspective likely emerges from the notion that the perceived value of waiting time surpasses that of access/egress time. The provision of highly frequent services could necessitate an extensive fleet of trains—potentially exceeding actual demand and incurring substantial costs. It's important to recognise that relying solely on one-dimensional solutions such as frequent services falls short. Thus, a comprehensive approach to HSR construction planning becomes important.

Moreover, in an effort to alleviate congestion during access/egress times, the implementation of a managed lane system on motorways, encompassing variable speed limits and hard shoulder management, emerges as a promising strategy (Cafiso et al., 2022). These approaches improve driving conditions with costs amounting to approximately one-third of the expenses associated with expanding motorways by an additional lane. However, it's crucial not to underestimate the investment required for the deployment of systems enabling enhanced management of transport infrastructure, such as Information and Communication Technologies on motorways or the European Rail Traffic Management System.

### 2.5.4 Planning, design and location of rail stations

The quality of design, maintenance, or operation of a rail station can profoundly influence both transfer time and the perceived duration of time for passengers. Essential to this is the presence of appropriate infrastructure that facilitates smooth movement within the station, encompassing design elements that enhance ease and speed of movement. Additionally, interventions aimed at making the time spent within the station more comfortable or productive play a significant role in shaping both clock time and passengers' perceived time. This cluster of factors encompasses solutions that target reductions in transfer times as well as enhancements in travellers' comfort. These solutions may involve increased space and comfort in waiting areas, improved lighting, and the implementation of surveillance cameras. Moreover, Loukaitou-Sideris, Peters and Wei (2015) highlight the importance of intermodal station. These stations serve as hubs where public transit users can transition between different modes of transport. The benefits derived from such stations include improvements in journey time and higher rates of ridership.

In addition to the planning and design of the station, the selection of the High-Speed Rail station's location emerges as a critical decision that significantly impacts access time. This decision entails a thorough consideration of numerous factors, including passenger demand, geometric and topological constraints, environmental considerations, economic constraints, and alignment with the country's economic growth strategy. Crucially, the access time from the urban area to the station stands out as a pivotal criterion in this determination.

Marti-Henneberg (2015) conducted an examination of how HSR stations are positioned in both European and Asian countries, as shown in Figure 2.4. The illustration delineates scenarios where stations are (A) located within and interconnected with the existing rail network, (B) positioned non-centrally yet complementary to traditional railway facilities within the same station, and (C) situated externally with exclusive High-Speed Train services. Notably, in Europe, France and Spain exhibit a higher prevalence of external stations compared to other countries. For an in-depth analysis of the policies governing HSR station location within EU nations, Martí-Henneberg and Alvarez-Palau (2017) provides comprehensive insights.

In Asian countries, the trend of situating many stations outside city centre dominates, with the exception of Japan. However, a significant drawback of this approach is that access/egress time to and from these outlying stations can constitute a substantial portion of total travel time for users (Diao et al., 2017). This is primarily attributed to the considerable costs and complexities associated with constructing new stations within urban areas, necessitating expensive land requisitions and resettlements. As a result, newly constructed HSR stations are often located on the outskirts of cities, or central HSR stations are often upgraded from conventional stations. Beyond mitigating these elevated costs, China, for instance, adopts the strategy of decentralising cities by positioning HSR stations in suburban areas (Wang et al., 2013).

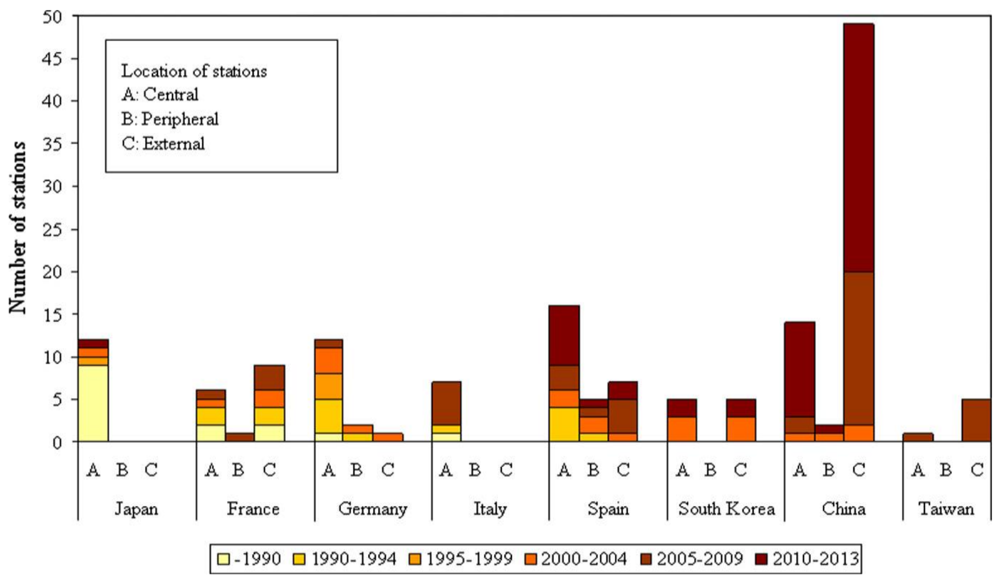


Figure 2.4 Location of HSR stations for some countries

*Source:* (Marti-Henneberg, 2015, p.149)

Another pivotal aspect to consider in planning, closely related to station location and journey time, is the urban area's structural configuration. The layout and design of urban environments play a crucial role in determining access/egress times to stations. Notably, the performance of High-Speed Rail systems in terms of access/egress time is most promising within densely populated and mono-centric cities, as exemplified by Tokyo and Paris (Albalate and Bel, 2012). However, the prospects are not as optimistic for polycentric cities characterised by dispersed populations. This challenge is particularly evident in the context of HSR development in the United States, where a significant number of cities boast a highly scattered urban structure.

Zhong et al. (2014) conducted an exploration into how urban structure influences the accessibility of HSR stations. To illuminate this, they compared the proposed HSR corridor between Los Angeles and San Francisco in California with the existing HSR corridor connecting Barcelona and Madrid in Spain. The study employed buffer zones around stations with radii of 5 km, 10 km, and 25 km. The findings indicated that a 10 km radius around Spanish HSR stations encompasses the most potential users, while the largest buffer zone (25 km radius) in California fails to include numerous potential users. It's important to note that this study compares the pre-existing Spanish line with the proposed Californian line, potentially overlooking the regenerative impact of new stations on land use. Despite this, the underlying dispersed nature of California's cities remains unchanged.

Addressing the challenge posed by the dispersed structure of cities, one potential approach involves considering the establishment of multiple stations within a city's boundaries. Yet, this proposition introduces a dilemma as it conflicts with the fundamental goal of high-speed train services: delivering shorter travel times. Hence, the responsibility rests on planners to strike a delicate balance. Their task revolves around determining the most optimal station location within the urban landscape that simultaneously minimises the number of stations along the line within the same urban area. This complex decision-making process highlights the effort to optimise travel times without compromising the efficiency of the high-speed rail system.

### 2.5.5 Pricing and ticketing

Purchasing tickets for public transportation constitutes a vital aspect of the journey, impacting both the pre-journey stage and the effort expended throughout the trip. When transitioning between various transport modes or services, additional time is typically required for ticket purchase or collection. This challenge is particularly pronounced in the context of multi-leg intercity journeys, where ticketing can emerge as one of the most challenging stages to successfully navigate.

Nonetheless, the overarching rationale behind offering "seamless" journeys to users is rooted in simplifying the planning and execution of multi-leg trips. Conceptually, the provision of integrated pricing and/or ticketing for individual components of intercity journeys has the potential to streamline the process. Such an approach facilitates pre-journey payments and information access, effectively expediting transfer times. With no need for additional time to purchase tickets or gather information during mode or service transitions, the travel experience becomes smoother.

Based on this integrated pricing and ticketing approach, in order to achieve coordination between different transportation options, Mobility as a Service (MaaS) become popular concept, which enable users to access, book and pay for multiple types of public and private transport options. It aims to provide door-to-door travel experience by combining different transport modes, such as trains, buses, and taxis. Researchers examined the opportunities and challenges of the concept for users and MaaS providers (Alyavina et al., 2022; Butler et al., 2021; Moyano et al., 2023). For example, for users, this integration might lead to reduced travel costs if integrated ticketing options involve discounts (Alyavina et al., 2022). However, older generations exhibit reluctance towards adopting MaaS because a significant proportion of individuals in this age group lack familiarity and experience with smartphones and online route planners (Butler et al., 2021; Moyano et al., 2023). As for MaaS providers, achieving coordination between different public and private operators can be barriers to this level of integration (Allard and Moura, 2016; Butler et al., 2021).

### 2.5.6 Travel planning and user information systems

The primary objective of the provided information revolves around furnishing travellers with comprehensive pre-journey details, enabling them to access relevant information during the planning phase and become aware of available options. This is particularly crucial for individuals undertaking multi-leg journeys, as the absence or scarcity of information can exacerbate the effort and time required for such journeys. The introduction of travel planner applications, like Google Maps, which offer insights into the transport system's connectivity and suggest alternative routes, significantly contributes to time-saving and mitigates passenger uncertainty.

Nevertheless, it's reasonable to infer that the collection of pre-journey information is predominantly undertaken by travellers who are well-versed in using the internet, smartphones, and web applications. Consequently, the tangible reduction in travel time is likely to be most pronounced within specific demand segments, such as business travellers and the younger demographic.

Additionally, real-time passenger information regarding schedules is as significant as the information provided during the pre-journey stage. Such real-time data aids in alleviating waiting stress, empowering passengers to optimise their time and activities. Collaborative peer-to-peer information networks concerning public transport service operations, including possible disruptions, enable passengers to seek alternatives and manage unexpected situations with reduced stress levels. The availability of travel planners on smartphones offers continuous routing assistance, minimising the likelihood of making incorrect travel choices or getting lost.

Moreover, enhanced onboard amenities, such as Wi-Fi internet access, and the ability to make well-informed seat choices prior to the trip contribute to a more convenient and comfortable travel experience, especially during lengthy journeys (Biosca et al., 2013).

### 2.5.7 Traveller comfort, safety and convenience

The comprehensive evaluation of travel experiences extends beyond only door-to-door travel time, encompassing factors like safety, convenience, reliability, and cost over the entire journey from origin to destination. Within public transport modes, "soft factors" significantly influence how users perceive travel time. As noted by Litman (2008), qualitative aspects such as travel convenience, comfort, and security substantially impact users' assessment of travel time unit costs. In fact, the inconvenience and discomfort experienced during travel often magnify the average travel time costs, as individuals are often willing to invest additional money or time for enhanced convenience and comfort. Consequently, the unit cost values associated with transit travel time are inherently variable, contingent on transfer requirements, conditions, crowding levels, and schedule reliability.

This variability carries significant implications for transportation planning, as travel time costs constitute an important component of transport project evaluations. However, conventional evaluation practices tend to overlook qualitative factors, assigning uniform time values regardless of varying travel conditions. Consequently, such practices underestimate the value of service enhancements that enhance comfort and convenience.

A noteworthy study conducted an assessment of passenger satisfaction with each dimension of the door-to-door rail journey and measures their relative importance, covering travel comfort, travel time reliability, station organisation and information, service schedule, dynamic information, price-quality ratio, accessibility, ticket service, personal safety and staff (Brons and Rietveld, 2009b). The findings indicated that travel comfort and time reliability emerged as the most important dimensions of the journey. The survey covers the period from January 2001 to December 2005, revealing a notable rise in satisfaction scores for travel time reliability. Interestingly the only aspect that declined over time is passenger satisfaction with staff. This outcome could be due to the growing trend of replacing traditional staff- involved tasks in rail travel such as purchasing tickets and obtaining information, with ticket vending machines and automated information points (Brons and Rietveld, 2009b).

## 2.6 Conclusion

In conclusion, this chapter begins by establishing a clear definition of HSR as outlined in relevant sources. Subsequently, the concept of accessibility was explained, including its quantification and the methodologies employed for its measurement. Moreover, this chapter reviews existing studies that investigate the realm of HSR accessibility, thereby highlights the preexisting knowledge within this realm. Additionally, a comprehensive exploration of the factors impacting influence over the accessibility of HSR systems is undertaken. The factors that have been identified encompass the following areas: (1) design characteristics of HSR corridors, (2) integration between transport networks, (3) infrastructure, service, and traffic management aspects, (4) the planning, design, and location of rail stations, (5) pricing and ticketing mechanisms, (6) travel planning and user information systems, as well as (7) considerations regarding traveller comfort, safety, and convenience. Notably, station location and its harmonious integration with public transportation networks stand out as particularly critical factors when assessing accessibility from a door-to-door journey time perspective. These factors heavily influence the ease of transfers and the overall efficiency of the travel experience. In the subsequent Chapters 5 and 6, these factors will be empirically examined to assess their real-world impact.

# Chapter 3 METHODOLOGY

## 3.1 Introduction

The literature has been advocating for the adoption of a door-to-door travel time approach in High-Speed Rail accessibility studies, as it provides a more accurate representation of journey time (Diao et al., 2017; Wang et al., 2013; Zhao, 2018). Currently, accessibility studies of intercity travel only consider on-board travel time and represent cities as single points, which ignores access and egress times within the cities. However, given that cities are areas, these intracity times are integral to intercity trips. Thus, a door-to-door travel time approach is proposed in this chapter to incorporate both inter- and intra-city trip segments, thereby offering a more comprehensive representation of total travel time.

The research methods used to examine the factors impacting HSR accessibility share common methodology approaches, which will be discussed in this chapter. However, it is important to note that each individual chapter adopted its unique configuration to address the specific research problems. Therefore, this chapter will only focus on the shared approach and methodology, while the individual chapters will address the unique techniques used to solve their respective challenges.

## 3.2 Door-to-door journey time approach

Door-to-door travel time (D2D) represents total travel time from origin to destination, which can be described for intercity journey as the integration of both the inter- and intra-city segments of a trip. When planning a long-distance intercity trip, travellers consider several factors such as cost, convenience, and the complexity of the entire journey from door-to-door, rather than just one element of it. For instance, while High-Speed Rail provides fast travel and relatively short travel time from station to station, the slow journey to and from the HSR station can significantly increase the overall door-to-door travel time, resulting in a poor travel experience (Banister et al., 2019). Therefore, it is important to consider the total journey time from door-to-door, and the speed of travel should be assessed in the context of the overall travel time (Givoni and Banister, 2012).

In the realm of rail travel, the concept of door-to-door journey time concept includes a multi-modal experience, integrating various travel modes. Literature on HSR intercity studies highlights the importance of door-to-door journey approach, usually evaluating the integration of inter-city segment with high speed trains and the intra-city segment with private cars. For example, Monzón, Ortega and López (2016) emphasise the crucial role of the first and last mile in door-to-door HSR trips. Wang et al. (2016) evaluate the accessibility impact of present and future HSR network in Jiangsu province, China, focusing on door-to-door journey time. Moreover, Zhao and Yu (2018) introduce a door-to-door travel time framework to assess the modal competition within intercity travel, using the proposed Dallas-Houston High-Speed Rail route as a case study. Likewise, Yu and Fan (2018) assess the accessibility impact of future high speed rail corridor on the piedmont Atlantic megaregion, incorporating the door-to-door journey time perspective. However, a limitation of all studies is that they only consider the car mode for access to a station and do not account for public transportation options. Based on the gap in the literature and in the context of this study's concentration on High-Speed Rail travel between cities, this study focuses on local public transportation at the intra-city level. The public transport system is relatively more sustainable transportation alternative, and lesser attention is given to the integration of intra and intercity of travel modes.

There are many different methods for the calculation of travel time. Salonen and Toivonen`s, (2013) study provides a good example of how different simplification levels can be applied to measure journey time for different transport modes, and how the choice of simplification level can affect the accuracy of the results. For public transport (PT), the first measure was a simple PT model that considered only the route geometry and hypothetical vehicle speed. The second measure, an intermediate PT model, also included the transfer time in addition to the measures in the simple model. The third measure, an advanced PT model, used up-to-date public transport data from the General Transit Feed Specification (GTFS) such as route, schedule, stops and stations to provide a more accurate calculation of journey time. For the car mode, the first, a simple car model, only considered the national road network and speed limits based on the geometry of the road.

For the car mode, an intermediate car model, included an additional consideration for congestion. The third, an advance car model, further disaggregated the journey time by considering the time required for walking to the car parking area. The comparison of different measurement shows that advance models for both transport modes are closer to the door-to-door journey time measurement, so give a more realistic result. Although Salonen and Toivonen`s study applied these methods on a transport network within an urban area rather than interurban travel, it is a good example showing the importance of simplification for an accurate result. Therefore, it was decided to apply an advance PT model for travel time calculation of our analysis. The advance model uses public transport timetable data, considering services, frequencies.

Disaggregation level of door-to-door intercity journey is usually different according to both the purpose of the research and the measurement precision required for the study. The more disaggregation could give the more complete and realistic representation of the total journey time of HSR travel, and then provide a better understanding of factors affecting each element. To avoid ambiguity between different interpretations of these journey legs, the following terminology is adopted in this thesis. The legs are access time, waiting time, in-vehicle time, transfer time and egress time.

- The door-to-door travel time represents the overall travel time, including all legs for intercity rail trips.
- The access time describes journey including at least one public transit vehicle before boarding on a train, journey time spent walking to the rail station or driving to the rail station in the origin city.
- The waiting time is the time that a passenger spends at stations before departing for train trip. The amount of this time changes depending on the integration between urban transport and inter-urban train service. Technically, more frequent services mean less waiting time.
- In-vehicle time of an intercity rail trip refers to total duration spent inside the train while travelling from the origin station to the destination station. It represents the cumulative time passengers are onboard the train during the entire journey, without considering any additional time spent during transfers or waiting at stations.
- Transfer time refers to the duration between transferring from one train to another during a journey that involves multiple train connections. Transfer times can vary based on factors such as distance between platforms, station layout, efficiency, and coordination between trains, physical and spatial characteristics of the station and its surroundings (Hadas and Ceder, 2010). For example, if passengers need to cross a street to transfer from one station to another, transfer time can be affected by waiting times at pedestrian crossing traffic lights and the design of pedestrian crossings, such as underpasses or overpasses. Another scenario is when passengers remain at the same station but have to physically move from one part of the station to another. Transfer time can also occur between two trains, involving a period of time between the arrival and departure of the trains.
- The term egress time describes the egress trip duration in the destination city.

Figure 3.1 illustrates these journey legs when inter- and intra-city segments are taken by high-speed train and public transport, respectively. A real-world example of a door-to-door long-distance journey stages is given for a trip from Rome to Milan in Table 3.1 below.

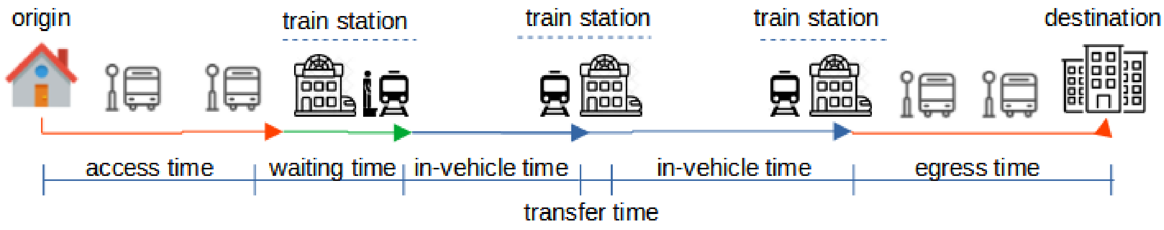


Figure 3.1 The components of door-to-door journey time

Table 3.1 A real world example of a door-to-door long-distance journey

| Trip stage | Station/stop | Date | Time | Travel with | Comments |
|---|---|---|---|---|---|
| **Access time** | Colosseo<br>Cavour<br>Rome Termini | Mon,24.04.21 | Dep 08:07<br><br>Arr 08:09 | metro | Service run by ATAC |
| **Waiting time** | Rome Termini | | | waiting | 11 min waiting |
| **In-vehicle time** | Rome Termini<br>Bologna Centrale<br>Milano Rogoredo<br>Milano centrale | | Dep 08:20<br><br><br>Arr 11:35 | HSR | Service run by Trenitalia |
| **Egress time** | Milano centrale<br>Centrale FS | | | walk | 2 min walking<br>9 min waiting |
| | Centrale FS<br>Gioia<br>Garibaldi FS<br>Moscova<br>Lanza<br>Cadorna FN<br>S. Ambrogio | | Dep 11:46<br>Dep 11:47<br>Dep 11:49<br>Dep 11:51<br>Dep 11:52<br>Dep 11:55<br>Dep 11:56 | metro | Service run by Comune di Milano |

## 3.3 Perceived or experienced time

In the current transport paradigm, travel time is generally considered to be wasted time and a disutility, therefore travel time savings are viewed as being beneficial to the individual traveller and to society. Less time spent travelling is assumed to convert ‘unproductive’ time into economically valuable time. However, travel utility (disutility) should not be only based on an objective measurement of time (based on Clock time) but also on the perception of the individual (based on Cognitive time) (Pineda and Lira, 2019).

The perceived or experienced time from a travellers’ perspective is an important concept within the field of transportation and travel behaviour. It refers to the subjective experience of time during travel, which can be influenced by a range of factors such as mode of transportation, trip purpose, and individual characteristics. For example, a minute spent in unpleasant conditions waiting for a bus may appear to be an hour, while an hour spent working, resting, or chatting while travelling on a comfortable bus or train may be pleasant.

There are some studies that examine the thought that travel time, rather than being wasted, can have a positive utility. In this sense, Mokhtarian and Salomon's (2001) pointed out that three different elements of journey might be the sources of positive utility derived from travel, “the activity of travelling itself, the activities at destination (trip purpose) and the activities conducted during the trip”. Mokhtarian and Salomon`s (2001) study challenges the traditional view that travel time is unproductive by highlighting the potential for travel to be an activity in itself. The traditional approach separates "activity time" from "travel time," but this overlooks the fact that travel can involve activities and that activities can involve mobility. For instance, in the case of leisure travel, individuals may travel purely for the sake of travelling because they find it enjoyable. In such cases, the trip itself is the activity and represents a source of utility and value to the traveller.

The perception of travel time as either a positive or a negative utility is largely determined by the overall travel experience, which is influenced by the availability of activities or opportunities for the passenger to engage in while in transit (Wardman and Lyons, 2016). If the travel environment provides opportunities for passengers or other uses of time beyond simply travelling, then travel time may be seen as more of a benefit than a cost or at least not so large a cost to the individual. Research has shown that travellers often use their travel time on public transport as an opportunity to work, conduct business, or enjoy the trip. For example, in a study titled "The use of travel time by rail passengers in Great Britain", a comprehensive survey was conducted to explore the utilisation of travel time by rail passengers and their perceived value of such activities (Lyons et al., 2007). The study's insights focus on distinct trends based on passengers' purposes of travel. Notably, the findings underscore that commuters exhibit a higher inclination towards leisurely reading during their travel time, compared to engaging in work or study activities. In contrast, business travellers predominantly allocate their travel time to work or study tasks, aligning with the demands of their professional engagements.

The studies reveal that leisure travellers are twice as likely as other passengers to devote a significant portion of their travel time to gazing out of the window or engaging in people-watching. Although this study is conducted prior to the widespread implementation of on-board Wi-Fi technology, the data unveils a key insight. It suggests that the use of time during travel is not entirely wasted for over three-quarters of rail passengers. This observation challenges the assumption that travel time is inherently unproductive, especially within the context of business travel performance evaluations. Consequently, it follows that the activities undertaken by passengers during their journeys possess the potential to mitigate the disutility often associated with travel time, thereby enhancing the overall travel experience.

Integrating the experienced time into transportation appraisal requires a shift in the approach of evaluating travel time savings solely based on objective measurements such as clock time. The generalised journey time concept is adopted to quantify the disutility of overall travel time. Therefore, the study can include not only the actual travel time on different modes of transport but also factors such as waiting time, transfer time between modes, time spent accessing and egressing from stations or stops, and potentially even factors like delays, service quality, and the overall convenience and comfort of the journey.

## 3.4 Generalised journey time

Generalised journey time (GJT) refers to a concept used in transportation planning and analysis to represent the total travel time experienced by individuals between two locations. Unlike the traditional approach that focuses solely on the actual time spent in transit, GJT consider additional factors that can affect the overall travel experience.

It's important to note that quantifying generalised journey time might be more straightforward for some components (e.g., travel time) than for others (e.g., comfort). Additionally, the weights assigned to each component might vary based on factors like user preferences, mode of transport, and trip purpose. The calculation of weight factors is usually driven from the value of travel time, which evaluates the benefits of travel time savings in monetary terms, considering the perceived value of time to individuals. Thus, the investigation of factors impacting value of time is important.

The concept of the value of travel time is often referred to by different terms, such as value of time or value of travel time savings. This can create confusion, but it's important to note that these terms all refer to the same underlying concept of the economic value placed on travel time. In the UK, the term value of travel time was chosen for consistency. In this study, the 'value of travel time' (VTT) is selected to represent this concept. Typically, time saved during travel constitutes a significant portion of the quantified advantages associated with transportation infrastructure initiatives and strategies. Consequently, inaccurately representing this aspect could potentially introduce distortions in the outcomes when assessing the value of time saved.

VTT can be influenced by various factors, such as the characteristics of the trip (e.g. distance, duration, journey purpose), demographic and socioeconomic characteristics of the traveller (e.g.

age, occupation, income), and the mode of transportation (e.g. car, walking, cycling, bus, train, flight) due to differences in comfort, cleanliness, reliability, level of personal control, and other quality attributes. Time of travel (e.g., weekday working hours, weekends) and travel conditions (e.g. congestion, crowding) can also affect VTT. Additionally, the productive use of travel time (e.g., the ability to work or use the internet while travelling) can also impact VTT.

First, traditionally, there are substantive differences between trip purposes, requiring the disaggregation of VTT based on trip purpose. The fundamental distinction for time value analysis is divided into two categories as described in the WebTAG guideline: working time (for business travellers), non-working time (for personal travellers and commuters) (DfT, 2023b). In the first case, VTT represents a cost incurred by employers due to the time spent on travel by employees, while in the second case, the cost is related to personal (unpaid) time spent on travel. Trips made during the working day are considered part of working time, whereas other travel activities are categorised as non-working time (such as trips for leisure, commuting, shopping, study, and so on).

The estimation methods employed to quantify VTT for business and personal travellers are different. However, delving into these nuances is beyond the scope of this current study. Incorporating this distinction in trip purposes into our analysis requires access to passenger counts and survey data that encompasses information about the specific objectives of trips. However, this essential dataset is unavailable for the corridor currently under construction, rendering its inclusion in the analysis unfeasible.

Secondly, research has suggested that engaging in multitasking and productive activities during travel can mitigate the discomfort associated with travel, consequently influencing the disutility of travel and potentially leading to a decrease in the perceived value of travel time (Lyons et al., 2013, 2007). However, these studies do not investigate how the worthwhile use of travel time affects VTT.  A recent study attempts to investigate the relationship between VTT and time use, but did not find any substantive variations in VTT based on time use, possibly due to endogeneity (Batley et al., 2019).

Wardman, Chintakayala and Heywood (2020) conducted a study focused on rail users and rail VTT. Their findings show that VTT varies depending on the activities undertaken while travelling. Specifically, when the time is used for meaningful activities, the VTT is lower, indicating that travellers have a lower willingness to pay to save travel time. However, the impact of time use on VTT has been quantified using a multiplier on the base VTT, which is typically defined as the time spent "doing nothing" while travelling. This multiplier is subsequently estimated for distinct activities conducted while travelling, such as reading printed materials or utilizing electronic devices. Incorporating this distinction into our analysis requires access to very detailed passenger survey data that encompasses information about how each individual used the journey time. However, again this kind of dataset is unavailable for the corridor currently under construction, rendering its inclusion in the analysis unfeasible.

Third, there are also studies that examine how the value of travel time varies depending on different travel time components. Warffemius et al. (2014) explored the value of travel time from a traveller's perspective by distinguishing between time as accessibility and time as valuable. Figure 3.2. illustrates the discrepancy between time spent and the quality of the travel experience. The x-axis shows the time invested in the journey, essentially the time needed for other activities, or accessibility. The y-axis represents the utility derived during the journey, ranging from practical tasks (like work) to pleasurable ones (like leisure activities). The graph's insights highlight that the journey's start and end points hold the highest value (and the lowest cost) as travel is typically less valuable than the primary activity itself. Within this framework, the most valued component of the journey is in-train time, followed by access and egress time, while waiting and transfer time rank as the least valuable experiences.

The x-axis reflects how travel time can be shortened to enhance accessibility, achieved by strategies such as faster driving, increased frequency, efficient connections, and well-designed transportation hubs. On the y-axis, while clock time remains unchanged, the value of time spent can be elevated by creating comfortable spaces within the train and station, where time feels to pass more quickly. Additional provisions that enhance the quality of travel and waiting times are also important. Services like shops, dining options, and live music performances at stations, along with amenities such as comfortable seats, adequate lighting, electrical outlets, and connectivity (like free Wi-Fi) on trains, all contribute to optimizing the utilisation of available time.

Román et al*.* (2014) conducted a study focusing on High-Speed Rail travellers along the Madrid–Barcelona corridor, revealing distinct values of time for various components of travel, including access/egress time, in-vehicle time, and waiting time. According to the multinomial logit model, the mean estimated values indicate rates of 15.78 €/h for in-vehicle travel time, 19.71 €/h for access/egress time, and 41.11 €/h for waiting time. These values can be presented as in-vehicle travel time multipliers, showcasing that access/egress, and waiting times are valued at 1.25 to 2.6 times that of in-vehicle time. Moreover, the research explores various trip purposes and provides an in-depth analysis of the value of time associated with different journey components based on the specific purposes of the trip. The findings with values of in-vehicle time multiplier are presented in Table 3.2 for business trips, where enterprises pay for the ticket, and tourism/commuting, where travellers pay for their own ticket. The value of time is notably higher for business trip. However, due to lack of passenger counts and survey data that encompasses information about the specific objectives of trips, this study only includes the mean value of time.

Table 3.2 Value of time of journey components for different journey purposes

| | **Tourism trip (€/h)** | **Business trip (€/h)** | **Commuting trip (€/h)** |
|---|---|---|---|
| In-vehicle time | 7.03 | 23.34 | 10.35 |
| Access/egress time | 10.00 | 28.33 | 10.00 |
| Waiting time | 10.77 | 73.68 | 10.77 |
| **Values of in-vehicle time multiplier** | | | |
| In-vehicle time | 1 | 1 | 1 |
| Access/egress time | 1.42 | 1.21 | 0.97 |
| Waiting time | 1.53 | 3.15 | 1.04 |

*Sources: (Román et al. 2014)*

Additionally, Wardman et al. (2016) undertook a meta-study encompassing multipliers associated with access and waiting time, measured in units of in-vehicle time, across European countries. These multipliers are distinguished based on journey distance, with no consideration given to travel mode. Notably, the study revealed for inter-urban journey that access time has a multiplier of 1.9, while wait time has a multiplier of 1.5. This differs significantly from the perspective presented by Warffemius et al. (2014) and also found by Román et al. (2014), who suggested that waiting time is the valuable experiences in a journey. A meta-study conducted by Wardman (2004) delved into the values of waiting and access time in the context of inter-rail journeys, showing  minimal differences between these journey components. Specifically, access time is assigned a multiplier of 1.11, while waiting time is slightly higher at 1.19, both measured in the unit of in-vehicle time.

Building upon these findings, this thesis conducts a sensitivity test with respect to the identified value of time from literature. This approach aims to comprehensively assess the impact of different journey stages and the impacts of different value of time values on results. The sensitivity test involves a comparison between the result of Wardman et al. (2016) and Román et al. (2014).  In this sensitivity test, values of time are assigned as weights for each stage of the journey based on in-vehicle time. Specifically, in the study of Román et al. (2014), access time is assigned a multiplier of 1.25, while wait time has a multiplier of 2.6. On the other hand, the study of Wardman et al. (2016) values access/egress and waiting times at 1.9 to 1.5 times that of in-vehicle time. By comparing these two studies, the sensitivity test aims to provide insights into the robustness and reliability of the findings, considering the variations in assigned values of time across different journey stages. Fourth, the value of time spent in vehicle can vary based on the mode of transportation—be it by car, walking, bicycle, bus, train, or plane. This variation arises from differences in passengers' perceptions of factors such as comfort, cleanliness, reliability, and other quality attributes. Hence, it is assumed that individuals using different modes like walking, bus, and underground transportation equally value their time within the access and egress stages.

Lastly, variations among types of train services may arise due to differences in the values of time associated with distinct journey purposes, and these purposes themselves differ based on the type of train service. Consequently, the value of time is expected to vary by different train services. However, in accordance with the WebTAG data book, it is assumed that all rail passengers, regardless of type of train service- whether conventional, regional, local, or high-speed trains- share the same disutility value.

Overall, the following assumptions in analysis will be adapted in this study.

- The value of time does not change based on journey purposes.
- The value of time is same for different type of train services; conventional, local and high-speed rail users.
- The value of time is same for all segment within the access and egress stages.
- The value of time is weighted for each journey stage in accordance with in-vehicle time. These are 1.25 and 1.9 for access and egress time, 2.6 and 1.5 for waiting and transfer time and 1 for in-vehicle time.

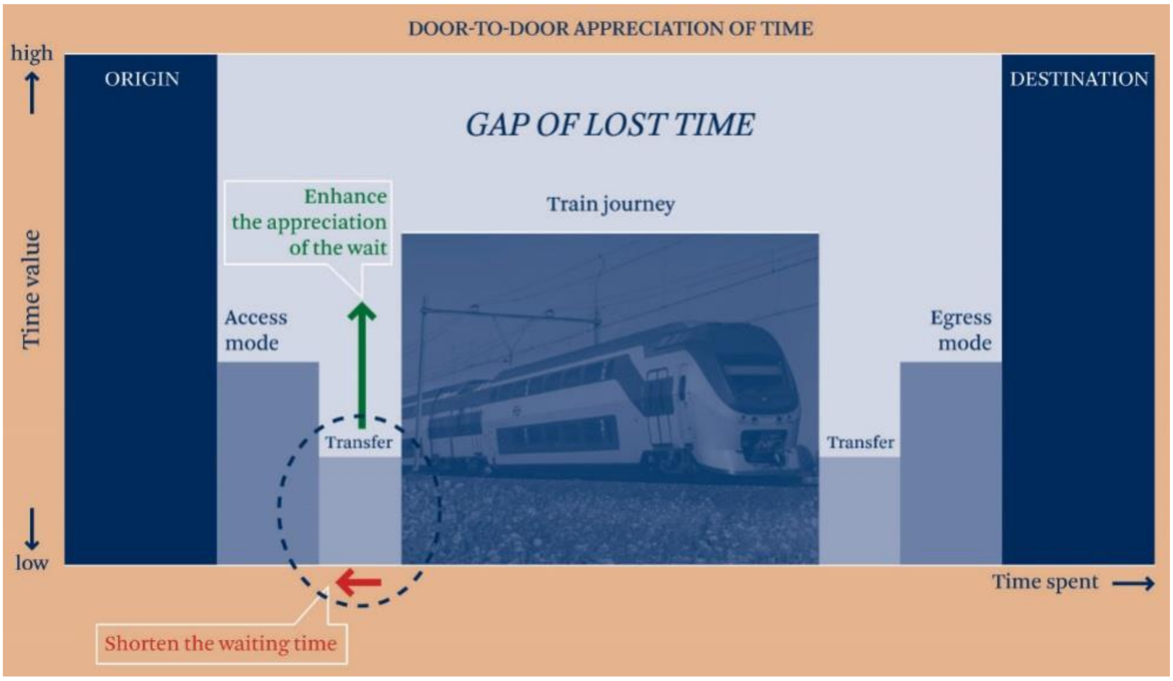


Figure 3.2 The discrepancy between time spent and experienced travel

*Sources:* (Warffemius et al., 2014)

## 3.5 Accessibility calculation

While there are several effective indicators for measuring accessibility, there is no universally accepted or preferred method for evaluating transportation options. Therefore, the selection of accessibility metrics should be based on various contextual factors, such as the specific goals, options being considered, and the data available (ITF, 2020).

The weighted average travel time (Jiao et al., 2014) is selected from the formulations available, See Chapter 2 section 2.3 for more detail about others. This metric is described the most appropriate option to evaluate the impact of the transportation infrastructure (Givoni, 2006; Monzón et al., 2013). It assesses accessibility at typically larger geographical scales and describes the degree of accessibility to various dispersed activities, encompassing both land use and transportation aspects at specific locations (Geurs and van Wee, 2004). The weighted average travel time indicator is responsive to changes in transport infrastructure, such as new roads, public transport services or bicycle routes. This study uses the generalised journey time as the impedance factor between OD points, so this indicator can be called as weighted average generalised travel time. It is expressed in minutes, which is a common unit of measurement for travel time, is easy to understand and interpret, and can be easily visualised using maps or other spatial tools (Yu and Fan, 2018).

When evaluating the attractiveness of destinations in high-speed rail accessibility studies, researchers commonly focus on population size (Bruzzone et al., 2023; Reggiani and Ortiz-Moya, 2022; Yu and Fan, 2018). Some studies prefer GDP as a metric (Weng et al., 2020), while others, propose a combined mass factor, typically the square root of a combination of population and GDP (Jiao et al., 2014; Yu and Fan, 2018). However, for the HS2 corridor case study, GDP data for each zoning system is unavailable. Moreover, employment opportunities are crucial for representing commuting patterns, but it may not fully represent the situation where a significant portion of the population uses high-speed rail for activities beyond commuting. Population is a comprehensive measure that includes both employed and unemployed individuals, providing a more holistic understanding of the potential user base. Therefore, the formulation is as follows:

$$\mathrm{WATT_i} = \frac{\sum_{\mathbf{j=1}}^{\mathbf{n}} \left(\mathbf{GT_{ij}} . \mathbf{P_j}\right)}{\sum_{\mathbf{j=1}}^{\mathbf{n}} \left(\mathbf{P_j}\right)}$$

where $WATT_i$ represents the weighted average generalised travel time of location i; GTij is the generalised travel time between location i and destination j; Pj is the population of destination j; n is the number of destinations The formulation of generalised travel time is as follows:

$$GT_{ij} = w1 \times at + w2 \times wt + w2 \times tt + ivt + w1 \times et$$

$GT_{ij}$: generalised travel time from i to j, at: access time, wt: waiting time at station to departure for first train, tt: transfer time between trains, ivt: in-vehicle train time in total, et: egress time, w1: weight for access time, w2: weight for waiting time

## 3.6 Review of tools to compute journey time

A key requirement of this project is to estimate travel time between a set of origin-destination (OD) pairs which can be generated for a range of motorised and non-motorised (cycling, walking) transport modes. Literature indicates that many transport analyses depend on accurate travel time estimates between OD pairs. These analyses are accessibility analysis (Pereira, 2019), demand forecasting model (Young and Blainey, 2018), land use and transport integration model (Sarri et al., 2023), and journey time reliability (Dixit et al., 2019). Thus, different route modelling tools have been developed to compute OD travel times or distances using public transport, private cars, bicycles. The most commonly used tools in literature include ArcGIS Network Analyst (Moyano et al., 2018), Open Trip Planner (Smith, 2018), and Google Maps API (Salonen and Toivonen, 2013; Jäppinen, Toivonen and Salonen, 2013). The features of these tools and which one is selected are explained below.

### 3.6.1 ArcGIS Network Analyst

ArcGIS Network Analyst toolbox is developed to analyse a network, calculate transit/walking service areas, and perform accessibility analyses. Main inputs of the tool are spatial data providing details of the road network and origin-destination locations to do analyses. Additionally, this toolbox in ArcMap can incorporate GTFS timetable dataset with the particular extension 'Add GTFS to a Network Dataset' developed by Morang (2020). Thus, this tool together with network analyst toolbox allows performing schedule-aware analyses for a specific time of day and day of the week. In the toolbox, users can customise the routing search whether to be the shortest distance or the fastest. As an outcome, the tool gives 1) total travel time between two points over a time 2) travel time between sets of points (OD cost matrix) for different time of day 3) preparing time-lapse animations which visualise images of the same location over time.

Although toolbox provides the total travel time between the origin and the destination, it does not give disaggregated results for all the trip legs. As a result, ArcGIS Network Analyst toolbox does not meet the key aim of this project, which is to estimate the duration of door-to-door journey components for intercity rail travel separately and assess the relative importance of these components using a series of case study corridors.

### 3.6.2 Google Maps API

Google Maps Application Programming Interface (API) provides a set of programming interfaces that enable developers to access and customize the Google Maps features, such as displaying maps, directions, and geocoding services. One of the key features of the Google Maps API is to calculate the journey time between two or more locations. This is achieved by using Google's routing algorithm, which considers several factors, such as real-time traffic conditions, road closures, and construction work, to provide an accurate estimate of the time required to travel between the locations. The Google Maps API provides a multi-modal route planning service for several modes of transport, including transit, driving, cycling, or walking.

This tool enables researchers to use the Google Distance Matrix API to estimate the OD travel time matrix. To calculate the travel time for each OD pair, the user sends a request including the OD coordinates, departure time, and type of transport mode type through the Google Maps API Server as an input, and the result is returned. However, there is a limit on the number of API calls from an IP address, usually set at 2,500 calls per day, which restricts the number of OD pairs that can be analysed. Furthermore, this tool does not allow for the addition of new public transport routes, station stops, or adjustments to frequencies, which limits its flexibility to accommodate changes in the transportation network. The ability to adjust the current network is essential when models are used to assess the potential impact of changes.

### 3.6.3 Open Trip Planner (OTP)

OpenTripPlanner (OTP) is a multi-modal trip planner that enables users to find the most efficient way to get from one point to another, considering all available public transport options. OTP is open-source software that can be used by transportation agencies, cities, and other organizations to create custom travel planning applications. OTP uses OpenStreetMap data as its primary data source, which is an open and freely available map of the world. OTP can also be configured to incorporate other data sources such as GTFS transit schedules, real-time transit data, and bike share systems.

The core functionality of OTP is route planning, which involves finding the fastest or shortest path between an origin and destination point based on a set of user-specified preferences. OTP supports a wide range of routing preferences, including transit mode preferences, maximum walk distances, preferred bike routes, and many others. OTP can calculate real-time journey times, incorporating factors such as traffic delays, transit schedule changes, and other unforeseen events. This is achieved through integration with real-time data sources, such as transit feeds and traffic APIs.

One of the key benefits of OTP is that it is open-source software, meaning that it can be freely used, modified, and distributed by anyone. This makes it an attractive option for transportation agencies and cities that want to create custom travel planning applications without having to develop their own trip planning software from scratch. It also allows developers to contribute new features and improvements to the software, making it more powerful and versatile over time.

### 3.6.4 Conclusion

Based on the examination of the routing tools above, OpenTripPlanner seems to be a better choice for this project than Google Maps API and ArcGIS Network Analyst toolbox. This is because OTP can disaggregate total journey time between OD pairs into different components, such as walk time, transit time, waiting time, and number of transfers. This is the main aim of the project - to calculate the duration of door-to-door journey components for intercity rail travel separately.

On the other hand, Google Maps API has limited access to the number of API calls from an IP address, and it is not possible to add new public transport routes, station stops, or adjust frequencies. Similarly, ArcGIS Network Analyst toolbox provides the total travel time between the origin and the destination, but it does not give disaggregated results for all the trip legs. This does not meet the key aim of this project, which is to estimate the duration of door-to-door journey components for intercity rail travel separately.

Therefore, based on the thesis's specific needs, OTP seems to be the most suitable tool for this project as it provides the necessary disaggregated results and allows for more control in producing as many routes as necessary.

## 3.7 Configuring OpenTripPlanner

OpenTripPlanner (OTP) uses a generalised cost approach that involves imposing penalties on interchanges and applying variable costs to the time taken by specific modes of transport, such as walking, in order to better represent travel behaviour (Smith, 2018). From this perspective, the "best" itineraries are not always the fastest ones. OTP uses certain criteria to determine the best route, which can be customised through arguments sent to the API. These arguments are stored in configuration files at the router level, namely build-config.json and router-config.json. The configuration options in these files are not mandatory and OTP will apply default values if any option or the entire file is missing. For example, the default walking speed is 4.8 kmph, unless another value is defined.

The workflow of OTP consists of two main stages. The first stage involves building the network of the study area using street network data from OpenStreetMap and transit stop/timetable data in GTFS format. This stage results in the creation of a fully functional route planner that supports multiple modes of transportation. The second stage involves querying the route planner with the desired origin and destination coordinates and the specific times of travel. This can be done either through the web interface of the route planner (as shown in Figure 3.3) or through the execution of a script. An overview of the entire process is provided in Figure 3.5. A tutorial paper for an introduction to OpenTripPlanner is provided by Young (2021).

The “otpr” R package is an API wrapper for the Open Trip Planner (Young, 2020). It enables users to send inputs to the OTP route planner and receive the results on the R platform. Users can specify various route search inputs such as the mode of transport, desired travel date, desired arrival or departure time, maximum walking distance, transfer time penalty, and minimum transfer time, walk reluctance parameter. Figure 3.4 shows an example query to call OTP and the resulting output; trip legs for a transit itinerary and specific disaggregated information for each leg.

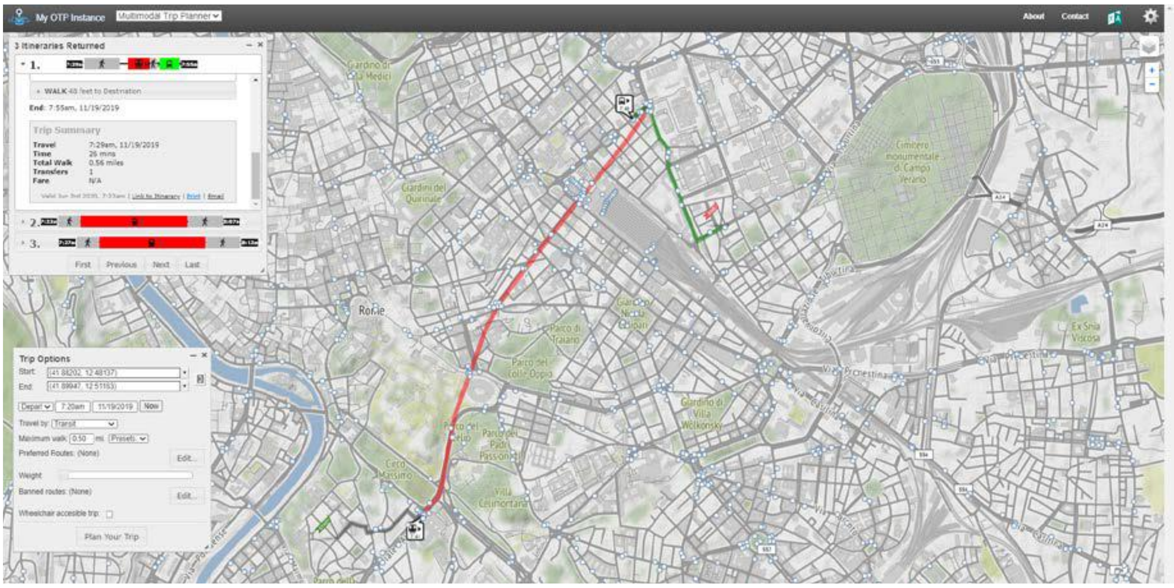

Figure 3.3 OpenTripPlanner instance and route request using the web interface

```
$errorId
[1] "OK"

$itineraries
                start                 end   timeZone duration walkTime transitTime waitingTime transfers
1 2019-11-18 21:43:00 2019-11-19 10:27:38 Europe/Rome   764.63    22.03         349       393.6         1

$query
[1] "http://localhost:8080/otp/routers/current/plan?fromPlace=42.09142,11.80082&toPlace=45.0694098192,7.67431720804025&mode=TRANSIT,WALK&date=11-19-2019&time=13:00:00&maxWalkDistance=1800&walk
Reluctance=2&arriveBy=TRUE&transferPenalty=0&minTransferTime=600"

$legs
            startTime             endTime   distance mode agencyName                  agencyUrl routeType routeId     headsign agencyId routeShortName duration routeLongName        fromName
1 2019-11-18 21:43:00 2019-11-18 23:03:00  72817.183 RAIL Trenitalia http://www.trenitalia.com/         2   2:377 ROMA TERMINI      OP3            FL5    80.00          <NA>    Civitavecchia
2 2019-11-18 23:03:00 2019-11-18 23:11:25    667.928 WALK       <NA>                       <NA>        NA    <NA>         <NA>     <NA>           <NA>     8.42          <NA>    Roma Termini
3 2019-11-19 05:45:00 2019-11-19 10:14:00 529323.823 RAIL      ITALO  http://www.italotreno.it.         2 1:100_1         rome      ITA           <NA>   269.00   Rome- Turin    Rome Termini
4 2019-11-19 10:14:01 2019-11-19 10:27:38    965.503 WALK       <NA>                       <NA>        NA    <NA>         <NA>     <NA>           <NA>    13.62          <NA> Turin Porta  Susa
  fromStopId fromStopCode   fromLon  fromLat           toName  toStopId toStopCode     toLon    toLat departureWait    timeZone
1 2:ROME8644            5 11.798843 42.08834     Roma Termini 2:ROME8436         27 12.506014 41.89750          0.00 Europe/Rome
2 2:ROME8436           27 12.506014 41.89750     Rome Termini  1:Termini       <NA> 12.501914 41.90123          0.00 Europe/Rome
3  1:Termini         <NA> 12.501914 41.90123 Turin Porta  Susa    1:Susa       <NA>  7.665889 45.07169        393.58 Europe/Rome
4     1:Susa         <NA>  7.665889 45.07169      Destination       <NA>       <NA>  7.674317 45.06941          0.02 Europe/Rome

> |
```

Figure 3.4 The example query to call OTP and result received from OTP

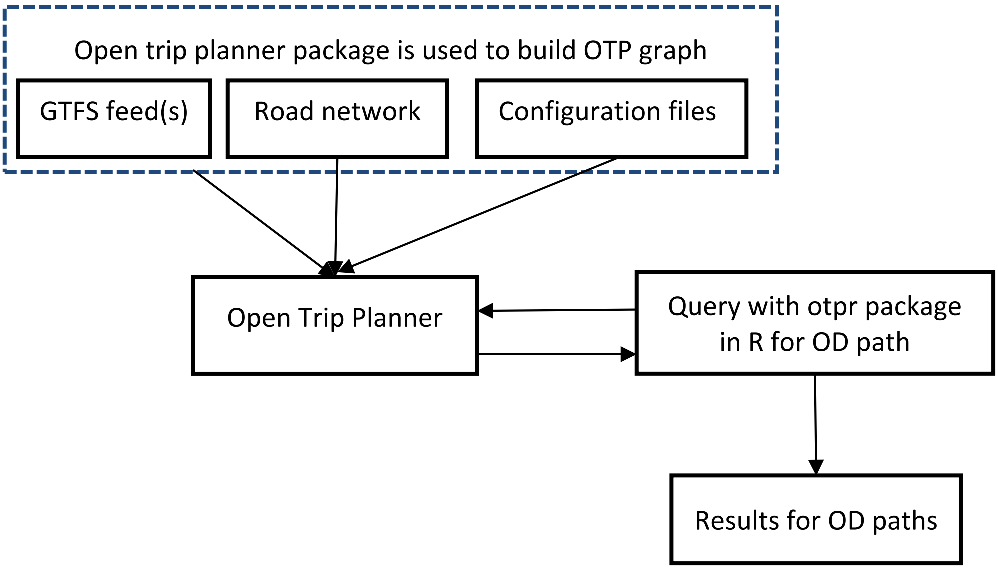


Figure 3.5 A schematic illustration of how to compute journey time

There are many options available to configure the OpenTripPlanner setup. This thesis uses the following criteria. If specific values are not provided for the criteria, default values will be used instead.

- minTransferTime: This parameter sets the minimum time required between exiting one transit vehicle and boarding another. Walking transfers are allowed between all stops within a certain maximum walking distance. The safety margin for transferring between vehicles is set to 10 minutes, and this value applies to all transfer types between public transport modes. Therefore, this value should be compatible with all modes of transport. The UK national rail timetable recommends a minimum allowance of 5 minutes for changing trains in the same station, with some exceptions for specific stations ("RailUK Forums," 2016). However, rail transfers are more reliable than bus changes due to separate right-of-way (Dixit et al., 2019), so 10 minutes seems reasonable value to use in all cases.
- transferpenalty: The transfer penalty (interchange cost) is a penalty applied to boardings after the first in OTP's routing algorithm. The penalty is measured in OTP's internal weight units. A high value for this parameter discourages transfers between different modes of transport. The value is taken as 10 minutes in the analysis, means that interchanges must achieve time savings of at least 10 minutes to be chosen (Smith, 2018).

The model must be run for a particular day and time. A holiday-free day should be chosen, with a full public transport service provided. The specific date will be provided in the analysis section of chapters. In order to account for the variation within days in schedules, three route searches were performed from origins to destination departing at 7:00am, 11:00am and 5:00pm. 7:00am can be a common departure time for people commuting to work or school in the morning rush hour.

11:00am may represent a mid-morning time when people may be travelling for leisure, and 5:00pm may represent the evening rush hour when people are commuting back home from work or school.

Then, the mean was taken of the three journey times. Example input values for travel time estimation between two points is given below.

- otp_get_times (otpcon, fromPlace = c (45.19681, 7.375659), toPlace = c (41.9056438, 12.508239), mode = 'TRANSIT', detail= TRUE, date = '11-18-2019', time = '07:00:00', arriveBy = TRUE, minTransferTime = 300, includeLegs=TRUE)

It is important to emphasise that OTP generates a set of multi-modal paths connecting origin zone Oi and destination zone Dj and then selects the optimal path among all options based on the pre-defined criteria inserted via router configuration and added manually via otpr package. With this way, it is possible to calculate journey time between OD by considering typical intercity travel behaviour. Users tend to plan their journey ahead with known schedules, rather than making an unplanned trip to the nearest train station and waiting for the departure.

## 3.8 OTP running time

The computation time required for analysis is a significant issue for this type of analysis. Identifying the shortest paths for a complex transit network and repeating the process for every Oi-Dj pair is computationally demanding. The time required for one query in OpenTripPlanner can vary depending on several computer features, including processor speed, memory, storage, and GPU. Also, the complexity of the query, the size of the transportation network, and the configuration of the OpenTripPlanner instance impact the computing time.

When dealing with large size of origin-destination matrix, the computational demands can be significant and can require long processing times, potentially taking several days to complete. Thus, multiple computers are used to run parallel processing, which allow us to distribute the computational workload across multiple machines and reduce the overall processing time. Specifically, we access multiple computers from the IRIDIS 5 high-performance computing (HPC) system, which is owned and operated by the University of Southampton. This system provides access to many interconnected computers with high-performance hardware and specialised software for managing large-scale computational tasks. Distributing the computational workload across multiple computers in this way can significantly reduce the time required to process the OD data.

In this study, the parallel computing operations were conducted on a cluster consisting of 30 computing nodes. Each node is equipped with 40 CPUs, totalling 40 cores per node and 64 GB of RAM. Specifically, the compute time for the case study detailed in Chapter 5, involving travel from the East Midlands to the West Midlands utilising an origin-destination matrix of size 616 by 1718, typically required approximately 15 hours to complete.

## 3.9 Conclusion

This chapter begins by introducing the unique disaggregation level of door-to-door intercity journeys, which has been tailored specifically for this thesis. It then proceeds to present the generalised journey time approach and the accessibility indicator that serves as the foundation for this study. Subsequently, the chapter delves into the notable tools frequently employed in the relevant literature, namely ArcGIS Network Analyst, Open Trip Planner (OTP), and Google Maps API. Among these tools, OTP was identified as the most suitable choice for addressing the project's requirements. Finally, the chapter provides detailed insights into the configuration of OTP, offering a comprehensive understanding of its implementation. In this manner, the chapter comprehensively outlines the overarching methodological aspects of the study.

# Chapter 4 RELATIVE IMPORTANCE OF TRAVEL TIME COMPONENTS

## 4.1 Introduction

The primary objective of this chapter is to investigate the relative importance of different journey time components. By understanding the significance of each component, decision-makers can make more informed and effective choices in alignment with their objectives. Quantifying the importance of the station-to-station part of intercity rail journeys compared to other components is of particular interest. To achieve this, the following questions will be addressed: "What are the proportions of overall journey time associated with each journey stage?" and "How do these proportions vary across a set of different corridors?" It is expected that the significance of each journey time component will vary across different corridors, the study will consider various factors, such as distance, route complexity, and infrastructure, to comprehend these variations.

To evaluate the impact of each journey stage, it is essential to calculate the door-to-door journey time. This chapter will present two methods employed to calculate the door-to-door journey time and subsequently analyse their advantages and disadvantages in the context of the thesis's objectives. A quantitative investigation will be conducted to compare these approaches, aiming to uncover their respective strengths and limitations.

In conclusion, this chapter aims to quantitatively investigate the relative importance of different journey time components. Through rigorous analysis and comparison of two calculation methods, this analysis will provide valuable insights into the magnitude of disbenefits associated with different legs, guiding decision-makers in prioritising interventions appropriately.

## 4.2 Door-to-door journey time calculation

In this study focused on HSR travel between cities, the intra-city travel to reach the HSR station can be accomplished through various transport modes, including public transport, car travel, and walking. However, as discussed in section 3.2, there is a limitation of previous studies that they only consider the car mode for access to a station and do not account for public transportation options. Thus, conversely, this study specifically excludes car travel and concentrate solely on the combination of public transport and walking as the modes of access and egress to the HSR station.

Previous studies examining the accessibility impact of HSR have primarily focused on station-to-station travel time (Chandra and Vadali, 2014; Jiao et al., 2014; Ortega et al., 2012). Some studies that have considered access and egress stages of the journey have only explored car access to the station (Monzón et al., 2016; Wang et al., 2016; Zhao and Yu, 2018). Alternatively, other studies have evaluated the access-egress stage up to the station without considering the entire door-to-door journey (Moyano et al., 2018; Rojas et al., 2018; Romero et al., 2021; Zhang et al., 2016).

To calculate the door-to-door journey time for intercity journey using the public transport system, studies commonly employ "Method 1 (aggregation)". This particular approach involves aggregating the travel times associated with various stages of the trip, including access to the HSR station, the main HSR journey itself, waiting time at the station, and egress from the HSR station (Wang et al., 2013). However, “Method 2 (disaggregation)" offers a more detailed analysis by simultaneously considering both intercity and intra-city travel, along with waiting and transfer times. This method considers the entire journey, from the origin to the final destination, and provides a more nuanced understanding of the door-to-door travel experience. It is important to note that both methods follow the schedule-based approach, which means using the public transport timetable data for journey time calculation.

### 4.2.1 Method 1 (aggregation)

This approach for estimating travel time between an origin-destination pair involves a segmented calculation of travel time for each part of the journey within the origin and destination cities, considering different transportation modes and station-to-station travel times, as shown in Figure 4.1. Access and egress time are taken to travel to and from HSR stations, in-vehicle time refers to the duration of travel between HSR stations. Additionally, to estimate waiting time at high speed rail stations, it assumes the average headway of train as the mean waiting time experienced by users (Wang et al., 2013). The assumption for waiting time may not always be realistic due to the presence of diverse passenger groups, variations in transit modes and service irregularities (Ansari Esfeh et al., 2021).

Subsequently, the average travel times for each of the individual segments are aggregated to obtain the total travel time. By calculating travel times for each segment individually, this approach might provide valuable insights into the precise durations of each segment, allowing for a detailed analysis of different parts of the journey. However, a limitation of this approach is that it may not fully capture the integration of journey stages and the impact of waiting and transfer times. As each segment is treated independently, potential interactions between different transportation modes and the overall journey experience may not be adequately accounted for, leading to a less comprehensive understanding of the total travel time.

Another notable limitation of employing Method 1 is encountered in scenarios where multiple HSR stations exist within the study areas. In such cases, a decision must be made to select only one station as the main hub for whole city. Alternatively, another process is needed to assign each zone to a specific station based on certain criteria, such as the nearest station (Monzón et al., 2016; Rojas et al., 2018) or generalised cost to station (Romero et al., 2021) which calculates the generalised cost associated with reaching each station from a given zone and then selects the station that offers the lowest generalised cost. This method is effective in identifying the station with the lowest access cost, but this might not be the station which delivers the lowed door-to-door journey time/cost, because in some circumstances using a more distant origin station may deliver a faster overall journey time to the final destination.

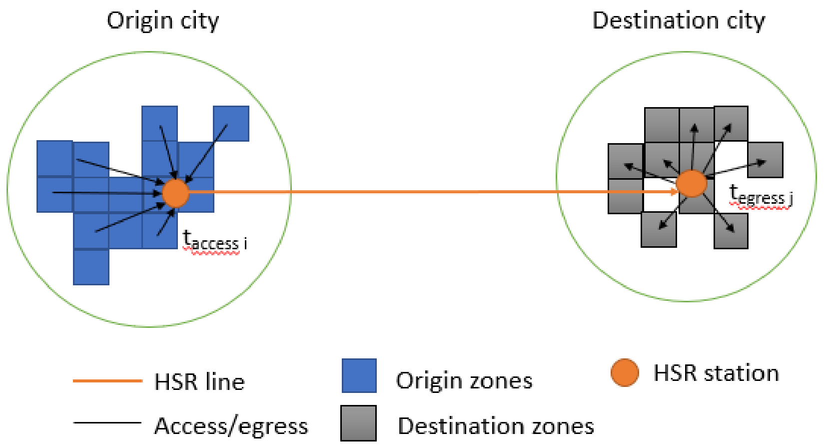


Figure 4.1 A door-to-door approach for Method 1

*Source: inspired by Moyano, Moya-Gómez and Gutiérrez (2018)*

### 4.2.2 Method 2 (disaggregation)

The second approach involves the simultaneous calculation of both intercity and intra-city journey times. This method considers the integration level of journey stages, as well as the impact of waiting and transfer time, recognising their variability based on the combination of utilised transport modes. By generating an optimal path connecting origin zone (Oi) and destination zone (Dj), a more comprehensive representation of the entire journey is achieved. This approach is advantageous because it aligns with the tendency of users to plan their journeys in advance, building on known schedules. Rather than travelling spontaneously to the nearest train station and waiting for departure, individuals often prefer to organise their travels based on known schedules.

One notable limitation of this approach lies in its computational complexity, particularly when compared to Method 1. In Method 1, separate calculations are performed for intra-city and inter-city journey times, resulting in a smaller number of origin and destination matrices. On the other hand, Method 2 combines these matrices, resulting in a much larger dataset. The process may require significant computing resources depending on the number of origins and destinations.

In summary, the first approach focuses on individual segment calculations and then aggregates them, while the second approach takes a more integrated approach, simultaneously considering intercity and intra-city travel along with waiting and transfer times. The second approach provides a more comprehensive understanding of the entire journey and may be better suited for capturing the impact of different transportation modes and their combinations on travel time. This chapter compares the outcomes achieved through the two methods across a set of case study corridors.

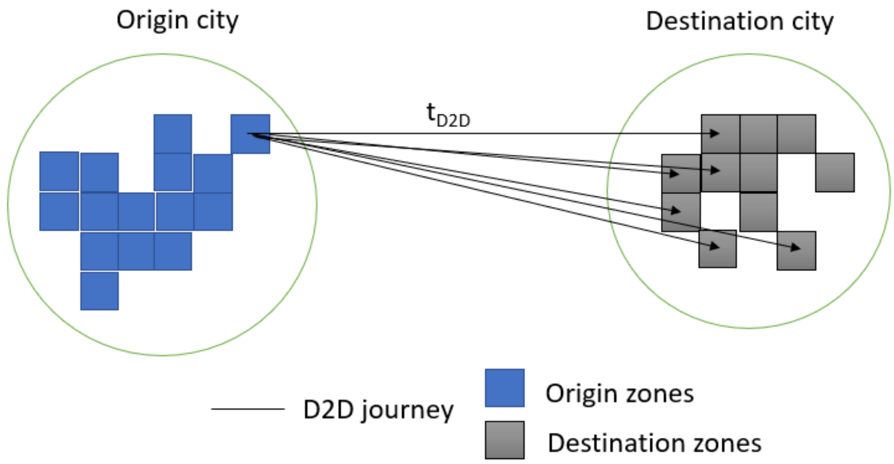


Figure 4.2 A door-to-door approach for Method 2

## 4.3 Definition of case study corridors

Chapter 2, Section 2.2 provides a comprehensive definition of high-speed rail systems and presents an overview of the operational and planned HSR corridors worldwide as of 2019, as conducted by the international union of railways (UIC, 2022a). Two HSR corridors used here to be used to show the procedure of how the methods presented above can be applied in different places and how transferable the applied methodology.

The corridor selection process followed three key steps. Firstly, an examination of operational corridors was undertaken based on a list provided by the UIC (2018). Secondly, to calculate journey times using the public transport system between the origin and destination points, the availability of General Transit Feed Specification (GTFS) datasets, an open public transport timetable data format, was assessed. Hence, the investigation focused on determining the existence of GTFS datasets for the public transport systems in the cities served by the HSR corridors. Unfortunately, Asian countries do not provide their dataset in GTFS format. Datasets for European cities where HSR corridors operational were investigated, and GTFS data was found for the Madrid-Barcelona and Hamburg-Berlin corridors. Thirdly, these two corridors exhibit variations in the number of HSR stations within their respective city areas, which can help to compare the differences of methods.

It is important to mention that while these corridors belong to the same continent, they exhibit distinct urban structures and economic characteristics, providing deliberate diversity for a comprehensive analysis of various factors and their influence on the HSR corridors.

### 4.3.1 Hamburg-Berlin corridor

The InterCity Express (ICE) is high speed rail system in Germany. The ICE network is known for its integration with existing rail lines. Figure 4.3 shows the dedicated high speed rail infrastructure in Germany. One notable corridor in the ICE network is the Hamburg-Berlin route, which began operation in 2004. This high-speed corridor covers a length of 286 km, and reaching a maximum speed of 230 km/h (UIC, 2022b). The non-stop station-to-station (between Hamburg Central Station and Berlin Central Station) travel duration for this route is approximately 1 hour and 50 minutes.

Hamburg has two stations, Hamburg Altona and Hamburg Central Station, connected by a high-speed rail line that goes to Berlin. Whereas, Berlin has three stations, Berlin Central Station, Berlin Spandau and Berlin Südkreuz station, connected by high-speed rail line that goes to Hamburg.

Public transport in Hamburg consists of buses, ferries, subways, light rail and heavy rail lines. The city's public transport network is coordinated by the Hamburg Transport Association, known as the Hamburger Verkehrsverbund (HVV), in collaboration with the Public Transport Authorities. The HVV regularly releases up-to-date timetable data in GTFS format for the entire network area every month via the link shown in the footnote[1]. The system includes four U-Bahn subway lines, six S-Bahn suburban lines, and 26 regional rail services, providing convenient transportation options to and from Hamburg and other cities in the area.

In addition to the rail network, Hamburg's public transport is further enhanced by an extensive range of bus services. These include metro buses, which offer frequent services within the city, as well as express buses, sprinter buses, and regional buses that connect to stations and surrounding towns, providing comprehensive coverage for commuters and travellers. Furthermore, Hamburg's

[1] Available at http://suche.transparenz.hamburg.de/?q=hamburg+gtfs&esq_not_all_versions=true &sort=publishing_date+desc%2Ctitle_sort+asc

unique geographical features include six ferry lines, which serve the harbour area and the River Elbe.

Berlin has a well-established public transport system, supported by multiple service providers. The primary provider, responsible for managing various modes of transportation, is the Berlin Transport Company, known as the Berliner Verkehrsbetriebe (BVG). BVG oversees the operations of the city's extensive U-Bahn subway lines, tram network, bus services, and ferry routes. BVG operates a total of 10 U-Bahn subway lines, 26 tram lines, 6 ferry routes, and many bus lines. Additionally, the Berlin transport network consists of S-Bahn urban rail system with 16 lines and 30 regional rail lines, operated by DB Regio AG, a subsidiary of Deutsche Bahn. DB Regio AG is responsible for operating commuter train services covering short and medium distances throughout Germany. GTFS data are available in the link shown in the footnote[2].


Figure 4.3 High Speed lines in Germany

*Source: (UIC, 2022b)*

[2]Available at http://transitfeeds.com/p/verkehrsverbund-berlin-brandenburg/213

### 4.3.2 Madrid- Barcelona corridor

Alta Velocidad Española (AVE) is a high-speed rail service in Spain operated by Renfe, the country's national railway company. The corridor between Madrid and Barcelona is approximately 506 km long. The trains on this route are capable of reaching a maximum speed of 300 km/h (UIC, 2022b). The station-to-station travel time between Madrid and Barcelona is approximately 2 hours and 32 minutes. Madrid Atocha is the only station serving for Madrid-Barcelona line. Barcelona Sants station is the station for HSR services in Barcelona.

The Madrid public transport network comprises a comprehensive range of services, including buses, the metro, a light rail/tram network, and heavy rail lines. Detailed information about these public transport services in Madrid can be found in the link provided in the footnote[3].

The bus network in Madrid is primarily operated by the Municipal Transport Corporation (Empresa Municipal de Transportes de Madrid, or EMT Madrid) and serves the capital city. In addition to the EMT buses, there are three distinct types of bus lines operated by different companies in the wider Community of Madrid: interurban buses, night buses, and urban buses. Interurban buses, often referred to as green buses, connect various municipalities within the region to the capital, with different transport companies managing these routes. Night buses, also known as 'owls' in the Community of Madrid, operate during the late hours, facilitating connections between the capital and different municipalities until the early morning. Urban buses primarily serve each of the major municipalities within the region.

The light rail system in Madrid consists of three lines, encompassing a total of 96 stations. Madrid's metro system, with 12 lines, ranks as the second longest metro system in Western Europe, after London's Underground. Additionally, Madrid benefits from a heavy rail network that connect the city and its metropolitan region. The provided link in the footnote[4] contains timetable data in GTFS data format for Madrid. However, it should be noted that this study does not include transit services provided by small transit agencies in the main municipalities of the region, as they do not provide GTFS data.

The Greater Barcelona area encompasses the city of Barcelona and also the 36 surrounding municipalities, also referred to as the metropolitan area. The transit network in Greater Barcelona includes several modes of transportation, including the metro, tram, funicular, buses, and heavy rail lines. The public transport services in Barcelona are managed by Transports Metropolitans de

[3] Available at https://www.redtransporte.com/madrid/
[4] Available at http://transitfeeds.com/l/167-madrid-spain

Barcelona (TMB), the primary public transit operator in the region. Complementing TMB's services, there are many regional bus routes operated by various companies throughout the Barcelona metropolitan area.

The metro system in Barcelona consists of 12 lines, known as L lines. TMB operates eight of these metro lines, while FGC (Ferrocarrils de la Generalitat de Catalunya) manages four lines. Tramvia Metropolita (TramMet) operates six tram routes, divided into Trambaix (T1, T2, T3) and Trambesòs (T4, T5, T6). Moreover, there are 15 heavy rail lines, known as Rodalíes or Cercanías trains, which serve the Barcelona metropolitan area. RENFE, the national railway operator, operates eight of these lines, while the FGC runs seven lines referred to as S lines. Funicular services in Barcelona are jointly operated by FGC and TMB.

The provided link[5] includes timetable data in GTFS format for buses and metro lines, tram routes. The timetable data in GTFS format for the heavy rail services provided by RENFE[6] and FGC[7] is available.


Figure 4.4 High Speed lines in Spain

*Source: (UIC, 2022b)*

[5] Available at http://transitfeeds.com/l/669-barcelona-spain
[6] Available at http://data.renfe.com/dataset?res_format =GTFS
[7] Available at https://www.fgc.cat/opendata/

## 4.4 Data Preparation

To calculate the journey time between origin and destination points, it is necessary to construct a multi-modal transportation network. This network relies on two essential datasets: spatial information detailing street networks and timetable data related to public transportation systems. By using these datasets, Open Trip Planner can accurately estimate the duration of journey stages such as access, waiting, and in-vehicle travel time. More detail about Open Trip planner is available in Chapter 3 Section 3.6.3.

The street network data can be obtained from OpenStreetMap (Openstreetmap, 2022), which is open-source mapping that provides free and editable geographic data to users all over the world. In order to incorporate public transport information into the analysis, timetable datasets in GTFS format are required for public transport within the cities (buses, light rail, metro) and between cities (conventional and high-speed train services). While defining corridors, the sources of public transport timetable for cities and conventional train are referenced, however GTFS datasets for high-speed train services are not online available for the case study corridors. The datasets have been manually created based on online timetable information. The structure of GTFS feeds has been learnt from the website (Gtfs.org, 2022).

The data required for creating datasets primarily encompasses the schedules of corridors and the geographic coordinates of HSR stations. Firstly, the schedule information was obtained from the European Rail Timetable website for HSR routes between Hamburg-Berlin and Madrid-Barcelona ("European Rail Timetable," 2019). The schedule of HSR services is based on the October 2019 edition on the website. The timetables used here are presented in Appendix A. Secondly, to complement the schedule data, the geographic coordinates of HSR stations were obtained from Google Maps, ensuring precise location information for the dataset creation process.

In order to focus on door-to-door travel time, it is crucial to establish a specific zoning system configuration that determines how the study area is organised and structured. The zoning system helps divide the study area into distinct zones or regions, facilitating the analysis and modelling of travel time between different origins and destinations. In this research, the GEOSTAT 1 $km^2$ reference grid with Eurostat population data were used (Eurostat, 2019). This zoning system offers a standardised and uniform structure that can be consistently applied across various geographical areas. Also, the availability of pre-existing grid cells and population data simplifies the initial setup and data preparation phases of the research.

The GEOSTAT 1 $km^2$ population grid only contains cells that are inhabited, and areas not covered by the grid are considered to lack residential population for the reference year 2011. The origin/destination points were derived from these grids by calculating the centroids. However, it is important to note using centroids as representative points may not accurately reflect the population distribution within each cell, particularly in sparsely populated areas (Moyano et al., 2018). Therefore, for future research, it is recommended to conduct a more comprehensive analysis to determine the optimal centre of mass for each cell, or select a different zoning system, if available, that can provide population weighted centroids.

## 4.5 Analysis and results

This section presents a quantitative investigation aimed at comparing the advantages and disadvantages of the methods described in Section 4.2. To achieve this comparison, two High-Speed Rail corridors are used, as outlined in Section 4.3.

### 4.5.1 Method 1

The primary calculation step for Method 1 involves determining the access and egress times to and from the HSR station using OTP for analysis. This process considers the time required to reach the station before a specific HSR departure and the time needed for egress immediately after the HSR arrives at its destination. Specific train services are used for both the Madrid-Barcelona and Hamburg-Berlin corridor to ensure an efficient travel experience.

In the Madrid-Barcelona corridor, each city has only one HSR station to serve the route. However, many areas located far from these stations face challenges in accessing them during the early morning hours due to limited or unavailable public transport services. To address this issue and ensure a seamless travel experience for passengers, specific train services that are not too early in the morning, have been scheduled from Madrid to Barcelona and vice versa. The departure times for these trains are set at 08:30 and 08:25, respectively, while the arrival times are scheduled for 11:15 and 10:55 for each respective journey. Based on these specific train services scheduled for the Madrid-Barcelona and Barcelona-Madrid, HSR trips take 2 h 45 min and 2 h 30 min, respectively.

The waiting time at a station, as commonly addressed in literature, is often approximated by assuming half the headway as the average waiting time (Ansari Esfeh et al., 2021; Yu and Fan, 2018). However, an alternative method presented in the literature offers a more comprehensive estimation of waiting time by considering the entire range of train services available throughout the day (Wang et al., 2013). This approach involves a formula that incorporates the actual service times of the first and last trains, as well as the total number of high-speed trains operating daily between two specific cities (stations). By accounting for these factors, this formula provides a more nuanced and accurate estimation of waiting time compared to the simplistic half-headway approach.

$$\text{waiting time} = (T^L - T^F) / (n-1)$$

n, represents the number of high-speed trains that operate daily from a specific city (station) i to another city (station) j, $T^L$ and $T^F$ are the time taken by the last and first train.

It is important to acknowledge a limitation in Method 1 due to the usage of OpenTripPlanner (OTP). The egress travel times are expected to commence simultaneously when the HSR services arrive at the station. However, due to variations in the schedule of the next local service, the actual start time of the journey chosen by OTP may deviate from our pre-set time. For instance, even though the train reaches Barcelona station at 11:15, which is the designated start time for the next journey, the OTP might select 11:37 as the start time, disregarding the time elapsed since the train's arrival, as shown in Table 4.1. However, the time difference between the train's arrival at the station and the actual start time of the subsequent intra-city journey should indeed be considered as an integral part of the actual overall journey, and it should be included in the egress travel time. Because with Method 1 door to door journey times are computed by summing the separate values calculated for different journey components, these 22 minutes are not included in the door-to-door travel time.

Likewise, a similar scenario emerges with access time to the station. For example, although the intra-city journey's arrival time is initially configured as 08:30 when setting up the OTP run, the generated arrival time in practice could be earlier due to the presence of existing public transport schedules for the access journey. Consequently, passengers might experience a waiting time at the station.

Table 4.1 Intra-city journey legs from station to destination

| | **Start Time** | **End Time** | **Mode** | **Departure Wait** | **Duration** | **From** | **To** |
|---|---|---|---|---|---|---|---|
| **1** | 11:37:36 | 11:41:59 | Walk | 0 | 4.38 | Barcelona Sants | Sants |
| **2** | 11:42:00 | 12:11:00 | Rail | 0.02 | 29 | Sants | Platja Castelldefels |
| **3** | 12:11:01 | 12:29:25 | Walk | 0.02 | 18.4 | Platja Castelldefels | Destination |

Table 4.2 demonstrates an application of Method 2 for a single OD pair to better illustrate this situation and provide a comprehensive overview of the overall journey. The 8$^{th}$ line of the table highlights that OTP automatically accounts for the departure wait time for subsequent intra-city journeys during the overall calculation. Thus, the egress travel time is accurately factored into the total journey duration.

Table 4.2 Door-to-door journey time calculated by OTP

| | Start Time | End Time | Mode | Departure Wait | Duration | From | To |
|---|---|---|---|---|---|---|---|
| **1** | 06:51:15 | 06:51:20 | Walk | 0 | 0.08 | Origin | Ctra.M501-Encrucijada |
| **2** | 06:51:21 | 07:25:28 | Bus | 0.02 | 34.12 | Ctra.M501-Encrucijada | Hospital |
| **3** | 07:25:28 | 07:33:31 | Walk | 0 | 8.05 | Hospital | Alcorcon |
| **4** | 07:49:00 | 08:11:00 | Rail | 15.48 | 22 | Alcorcon | Atocha |
| **5** | 08:11:00 | 08:15:08 | Walk | 0 | 4.13 | Atocha | Madrid Puerta De Atocha |
| **6** | 08:30:00 | **11:15:00** | Rail | 14.87 | 165 | Madrid Puerta De Atocha | Barcelona Sants |
| **7** | 11:15:00 | 11:19:02 | Walk | 0 | 4.03 | Barcelona Sants | Sants |
| **8** | 11:42:00 | 12:11:00 | Rail | **22.97** | 29 | Sants | Platja Castelldefels |
| **9** | 12:11:01 | 12:29:25 | Walk | 0.02 | 18.4 | Platja Castelldefels | Destination |

Table 4.3 presents the average contribution of each journey stage to door-to-door journey time for trips in both directions on the Madrid-Barcelona corridor. It is important to note that due to differences in the service characteristics between the two corridors, there is a 15-minute disparity in vehicle travel time for the HSR service, which impacts the overall contribution of other components. In both directions, the waiting time is 25 minutes, assumed to be constant across all zones. The average access and egress times for Madrid are higher than those for Barcelona, primarily due to Madrid's wider coverage area and larger metropolitan region.

The average access and egress times to and from the Barcelona HSR station are almost identical, whereas there is a notable difference of nearly 7 minutes in the average access and egress times to and from the Madrid HSR station.

Table 4.3 Contribution of each stage to D2D journey time for trips in both directions on the Madrid-Barcelona corridor

| Origin | Destination | Average travel time (minutes) | | | | |
|---|---|---|---|---|---|---|
| | | D2D travel time | Access time | Waiting time | In vehicle time | Egress time |
| Madrid | Barcelona | 297.5 | 56.7 | 25 | 165 | 50.8 |
| | | | *19%* | *8.4%* | *55.4%* | *17%* |
| Barcelona | Madrid | 289.4 | 50 | 25 | 150 | 64.4 |
| | | | *17.3%* | *8.6%* | *51.8%* | *22.2%* |

Figure 4.5 visually illustrates the spatial distribution of how access and egress contribute to the door-to-door travel time in corridors. The yellow grids on the map are well connected to the HSR stations. Conversely, the darkest areas on the map regions with the lowest accessibility to the HSR stations. Regarding the grey grids, the journey time was not calculated by OTP due to the unavailability of public transport data in Barcelona for these specific areas. While this absence of relevant data hinders obtaining accurate estimation of average travel times, it is important to note that the primary focus of this study is not on achieving precise estimations. Instead, the

study aims to highlight and analyse the differences that arise from the methods used to calculate door-to-door journey times.

In Barcelona, the spatial distribution of access and egress contributions to the overall journey time is similar. However, the situation is notably different in Madrid, where distinct differences between access and egress contributions can be observed. Especially, the zones located on the north-west of Madrid Atocha HSR station experience higher egress times compared to access time to the station.

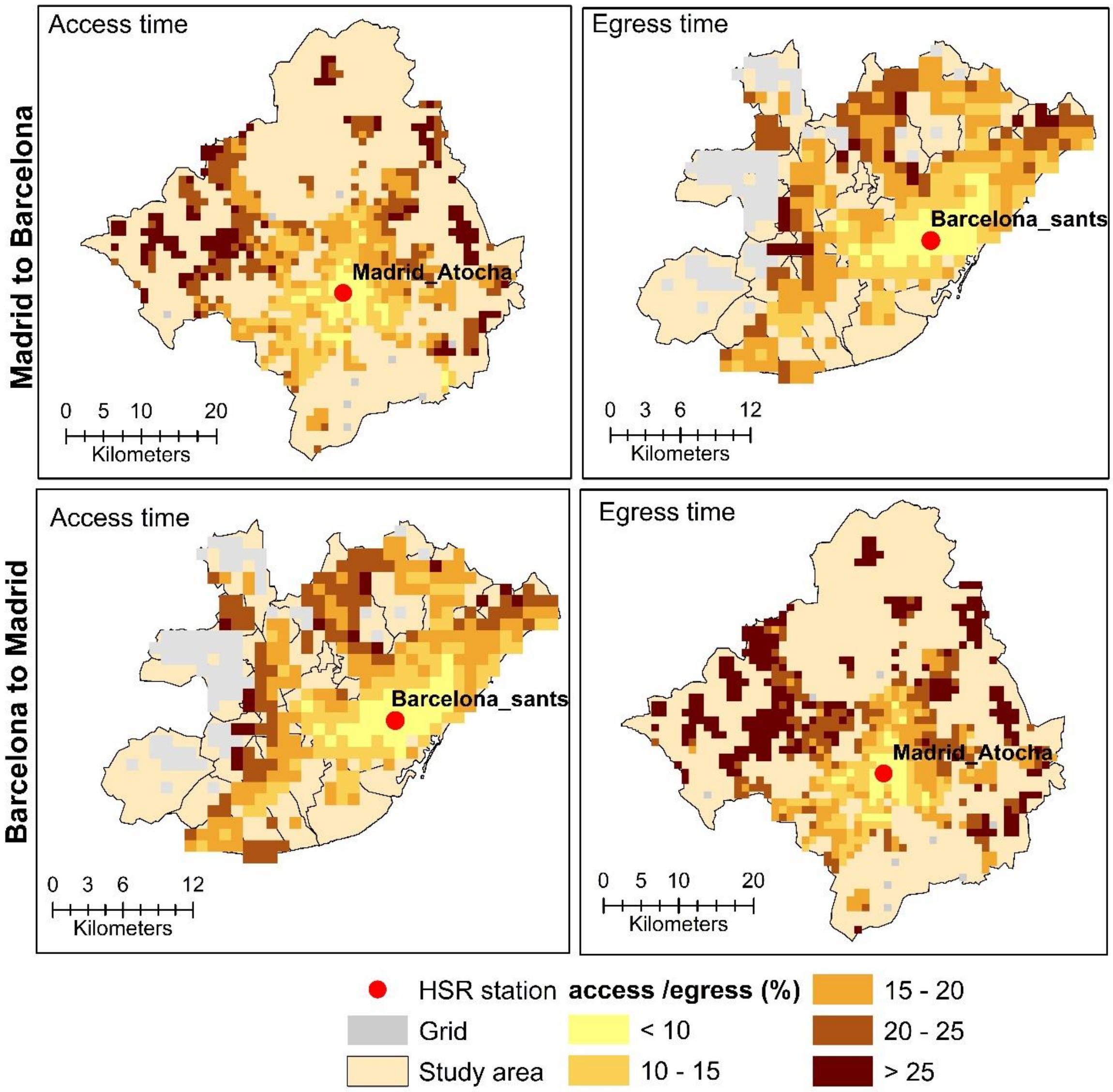


Figure 4.5 Spatial variation of access and egress contribution to D2D time in the Madrid-Barcelona corridor and vice versa

In the Hamburg-Berlin corridor, there are two stations (Hamburg Altona, Hamburg Hbf) in Hamburg and three (Berlin Spandau, Berlin Hbf, Berlin Sudkreuz) in Berlin serving the route. As mentioned earlier, when calculating access and egress times to/from the stations in the Hamburg-Berlin corridor, two primary approaches can be considered. The first approach involves designating a single station as the main hub for the entire city, whereas the alternative approach takes a more realistic approach by implementing a process to assign each zone within the cities to the nearest station based on journey time. The second approach is preferred due to its better representation of real-life scenarios. By considering the geographical distribution of zones and proximity to the stations, this approach offers a more accurate reflection of how passengers naturally access and egress from the transportation network.

The journey between Hamburg and Berlin involves multiple intermediate stations, leading to train services scheduled at different times and resulting in varying in-vehicle times for passengers travelling between these stations. To calculate the average in-vehicle time for the entire Hamburg-Berlin and Berlin-Hamburg routes, it is considered the train services operating between the first and last stations, 08:20 - 10:37 and 08:27 - 10:38. The average in-vehicle time is calculated as 115 minutes for the Hamburg-Berlin journey and 110 minutes for the Berlin-Hamburg journey. However, it's essential to acknowledge that the actual journey time can range between 95 minutes and 137 minutes, depending on the specific stations used for departure and arrival. Average waiting time is calculated as described above.

Table 4.4 presents the average contribution of each journey stage to door-to-door journey time for trips in both directions on the Berlin-Hamburg corridor. In both corridors, a constant waiting time of 45 minutes is assumed across all zones. Interestingly, Berlin exhibits lower average access and egress times compared to Hamburg, despite Berlin having a wider coverage area. This difference can be attributed to the advantage of Berlin having three HSR stations, providing passengers with enhanced accessibility options to reach the stations efficiently.

Table 4.4 Contribution of each stage to D2D journey time for trips in both directions on the Berlin-Hamburg corridor

| **Origin** | **Destination** | **Average travel time (minutes)** | | | | |
|---|---|---|---|---|---|---|
| | | **D2D travel time** | **Access time** | **Waiting time** | **In vehicle time** | **Egress time** |
| Hamburg | Berlin | 262.3 | 54 | 45 | 115 | 48.3 |
| | | | *20.58%* | *17.15%* | *43.8%* | *18.4%* |
| Berlin | Hamburg | 258.6 | 48.6 | 45 | 110 | 55 |
| | | | *18.8%* | *17.4%* | *42.5%* | *21.2%* |

Figure 4.6 shows the spatial distribution of how access and egress contribute to the door-to-door travel time in corridors. As expected, the presence of multiple HSR stations extends the accessibility of regions to the HSR system. However, it is noteworthy that these additional stations also introduce extra in-vehicle time to the journey, as train needs to make more stops along the route. In both cities, a similarity is observed in the spatial distribution of access and egress contributions to the overall journey time.

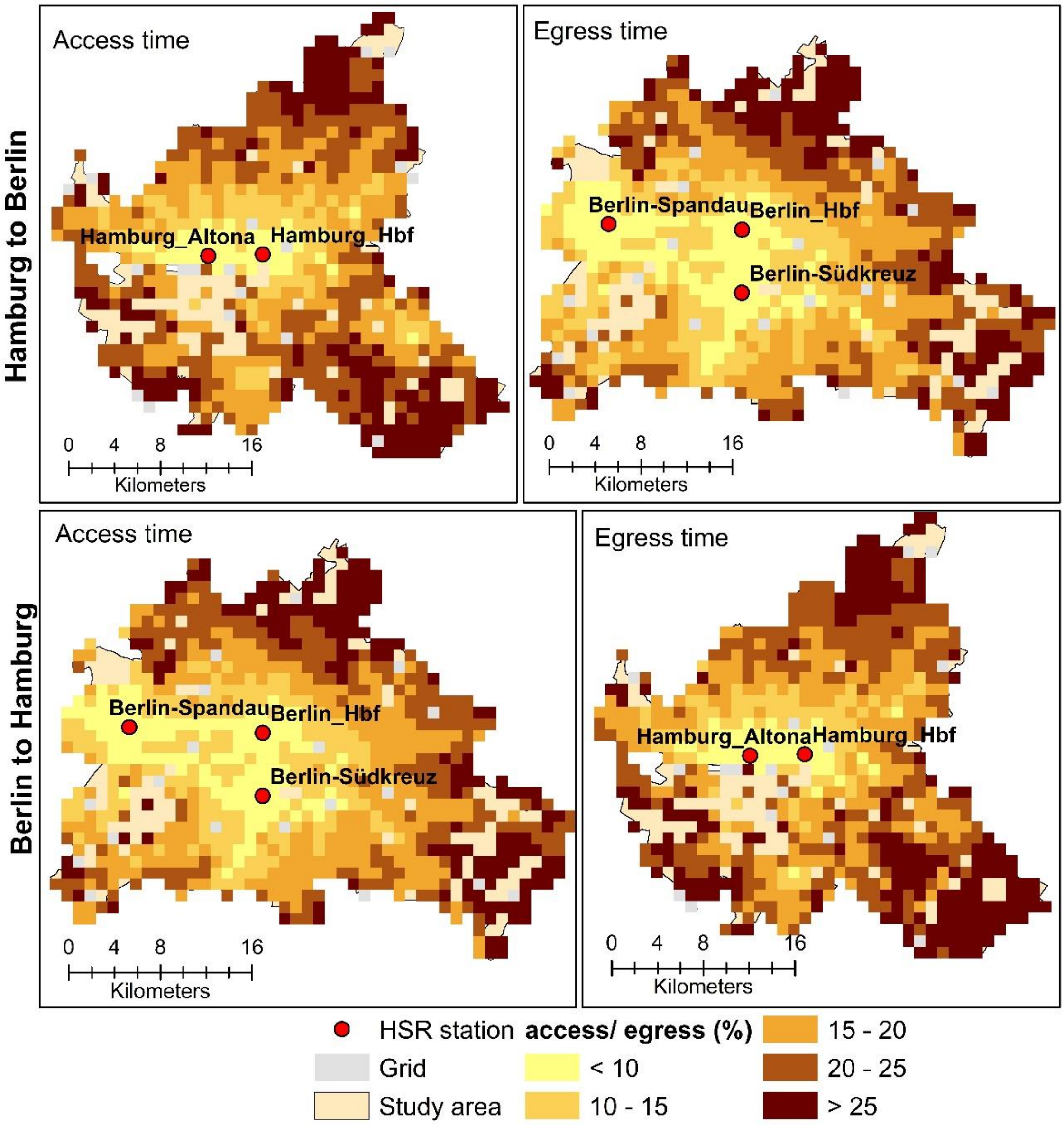


Figure 4.6 Spatial variation of access and egress contribution to D2D time for trips in both directions on the Berlin-Hamburg corridor

### 4.5.2 Method 2

This method simultaneously computes travel times for both intercity and intra-city journeys. It considers the level of integration between different stages of the journey and recognises the varying effects of waiting and transfer times. The primary benefit of the holistic calculation approach is its ability to account for the fluctuating impact of waiting times, as opposed to assuming a constant waiting time for all zones within the city. This consideration leads to a more accurate and realistic estimation of travel times, reflecting the actual conditions experienced by passengers in different parts of the city.

Secondly, this thesis aims to consider the disutility associated with different journey components, which show differences due to travel comfort, crowding, reliability and duration for different modes. To achieve this, it is essential to accurately disaggregate the door-to-door intercity journey time.

In Method 1, the door-to-door journey time is separated into three parts: the access/egress time to and from the High-Speed Rail station, the in-train time between HSR stations, and the waiting time at HSR stations. However, this approach includes journeys made by the local rail network within the access and egress part, which might not adequately represent the overall disutility experienced, as railway travel is often more comfortable than other local public transport options like buses, light rail, and subways.

Method 2 is able to address this limitation and better account for the disutility of different journey components. This approach considers the railway network as a whole system, and all sections of the door-to-door journey which involve a train (whether high speed or conventional) are treated as a distinct part/segment. The subsequent steps involve summing up the entire rail journey to calculate the in-vehicle time between train stations and the transfer time between trains as additional components. While there might be potential variations in disutility between high-speed trains and local trains due to differences in speed, for the scope of this study, they are considered equal. Moreover, the waiting time is now determined based on the first railway station rather than the HSR station.

Furthermore, it is important to note that Method 1 focuses exclusively on the usage of the HSR system, which may result in overlooking the availability and potential benefits of conventional rail options in certain zones for reaching the destination city. In reality, some zones within the region might have existing conventional train services that offer better accessibility to various destinations. Given that the primary objective of this thesis is to examine the impact of a future HSR network across a region, it is crucial to ensure comparability with existing conventional train services, if they are available. By considering both HSR and conventional rail options, the analysis can provide a comprehensive evaluation of transportation alternatives, accurately assessing the potential winners and losers resulting from the future HSR network.

Table 4.5 provides insights into the breakdown of travel times and the relative significance of each journey stage for the two city pairs considering journeys between each pair in both directions, including an additional stage that accounts for the transfer time between conventional trains and HSR trains. This supplementary stage offers valuable insights to assess the interconnectivity level between the conventional and HSR train systems. It is possible to say that transfer time for trips in both directions on the Madrid-Barcelona corridor is important part of the journey with average 40 minutes. Further improvement in the timetable integration can enhance the overall travel experience and ensure a smooth journey for passengers

Indeed, a notable and consistent observation across all cities is the consistently longer duration of egress time compared to access time. To illustrate, consider Hamburg, where the average access time is 48.7 minutes, whereas the egress time is notably longer at 67.7 minutes. This trend can potentially be attributed to the waiting time passengers experience while waiting for the local public transport system. During the egress phase, upon reaching the HSR station, passengers might encounter a wait for the subsequent available local public transport options, such as buses or light rail, needed to complete their journey to the final destination. This waiting interval for the connecting transport contributes to the overall extended egress time duration.

Table 4.5 Contribution of each stage to door-to-door journey time

| **Origin** | **Destination** | **Average travel time (minutes)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **D2D travel time** | **Access time** | **Transfer time** | **Waiting time** | **In vehicle time** | **Egress time** |
| Hamburg | Berlin | 252 | 48.7 | 15.3 | 20.2 | 129 | 38.8 |
| | | | *19.3%* | *6.1%* | *8%* | *51.2%* | *15.4%* |
| Berlin | Hamburg | 260 | 27.5 | 20.8 | 9.7 | 133.4 | 67.7 |
| | | | *10.6%* | *8%* | *3.8%* | *51.5%* | *26%* |
| Madrid | Barcelona | 331 | 37.8 | 39 | 12 | 206.6 | 35.6 |
| | | | *11.4%* | *11.7%* | *3.6%* | *62.4%* | *10.7%* |
| Barcelona | Madrid | 331 | 26.7 | 40 | 7 | 205 | 52.7 |
| | | | *8%* | *12%* | *2%* | *62%* | *16%* |

In Figure 4.7, a visual representation is provided that showcases the spatial variation of access, egress, waiting, and transfer contributions to the door-to-door travel time within the Hamburg-Berlin corridor. Notably, waiting times are significantly reduced in the vicinity of railway stations. It is essential to highlight that these waiting times primarily result from local public transport services and differences in the first rail departure times. However, the zones located around the stations on the northeast of Hamburg HSR stations exhibit the highest contribution of transfer time. This indicates that passengers travelling through these zones experience longer transfer durations between trains.

Figure 4.8 shows the spatial variation of access, egress, waiting, and transfer contributions to the door-to-door travel time in the Barcelona-Madrid corridor. Access and egress times typically show lower values in the vicinity of railway stations. It is important to note that the transfer time visualised in the map represents the average time taken to travel from the origin zone to all destination zones, including the average transfer time within the destination city. Between Hamburg and Berlin, train transfer is so common and always has contribution to overall journey. While access and waiting times play essential roles in determining the overall journey experience, their contribution is lower compared to transfer time.

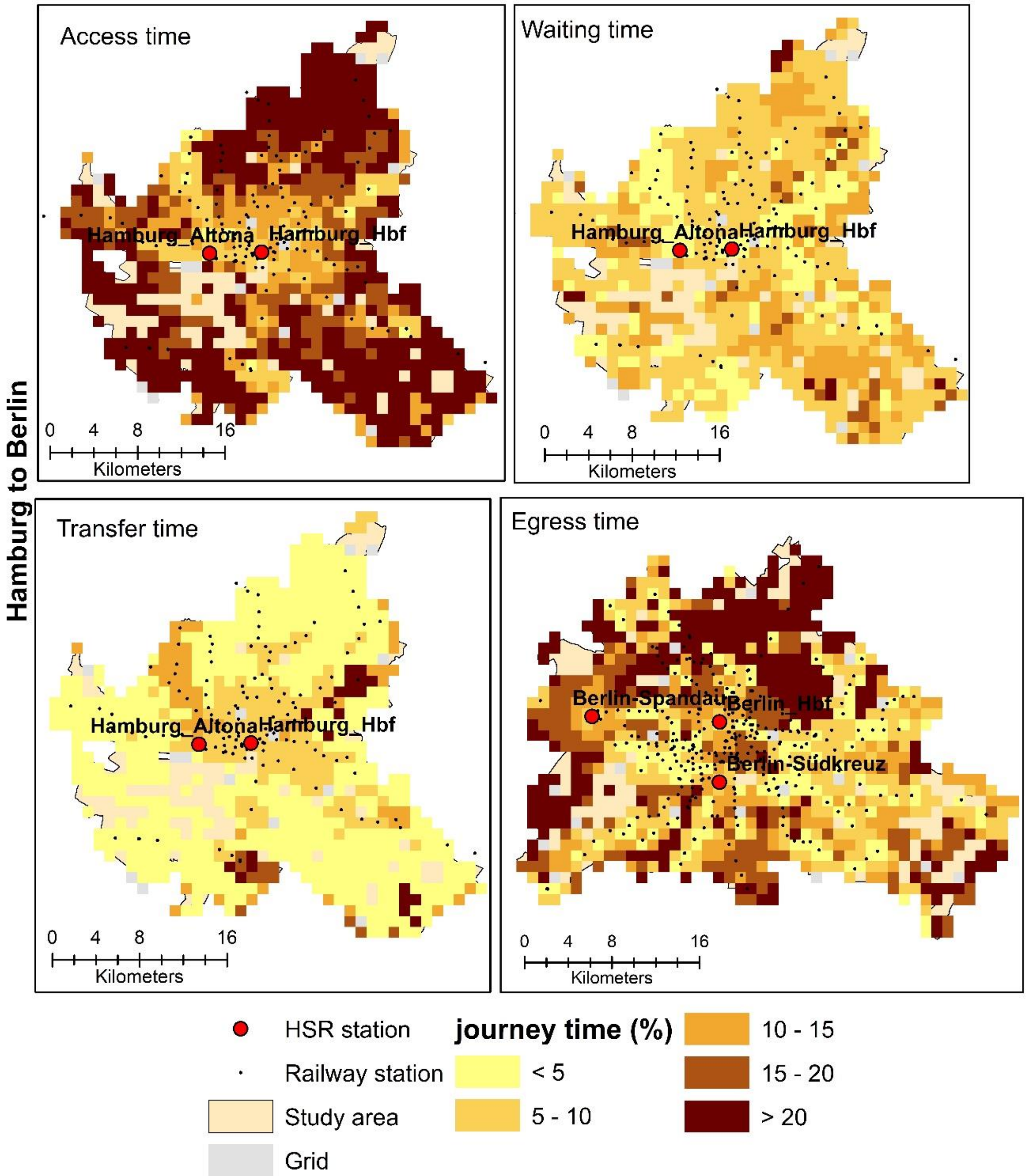


Figure 4.7 Spatial variation of access, egress, waiting and transfer contribution to D2D time in the Hamburg-Berlin corridor

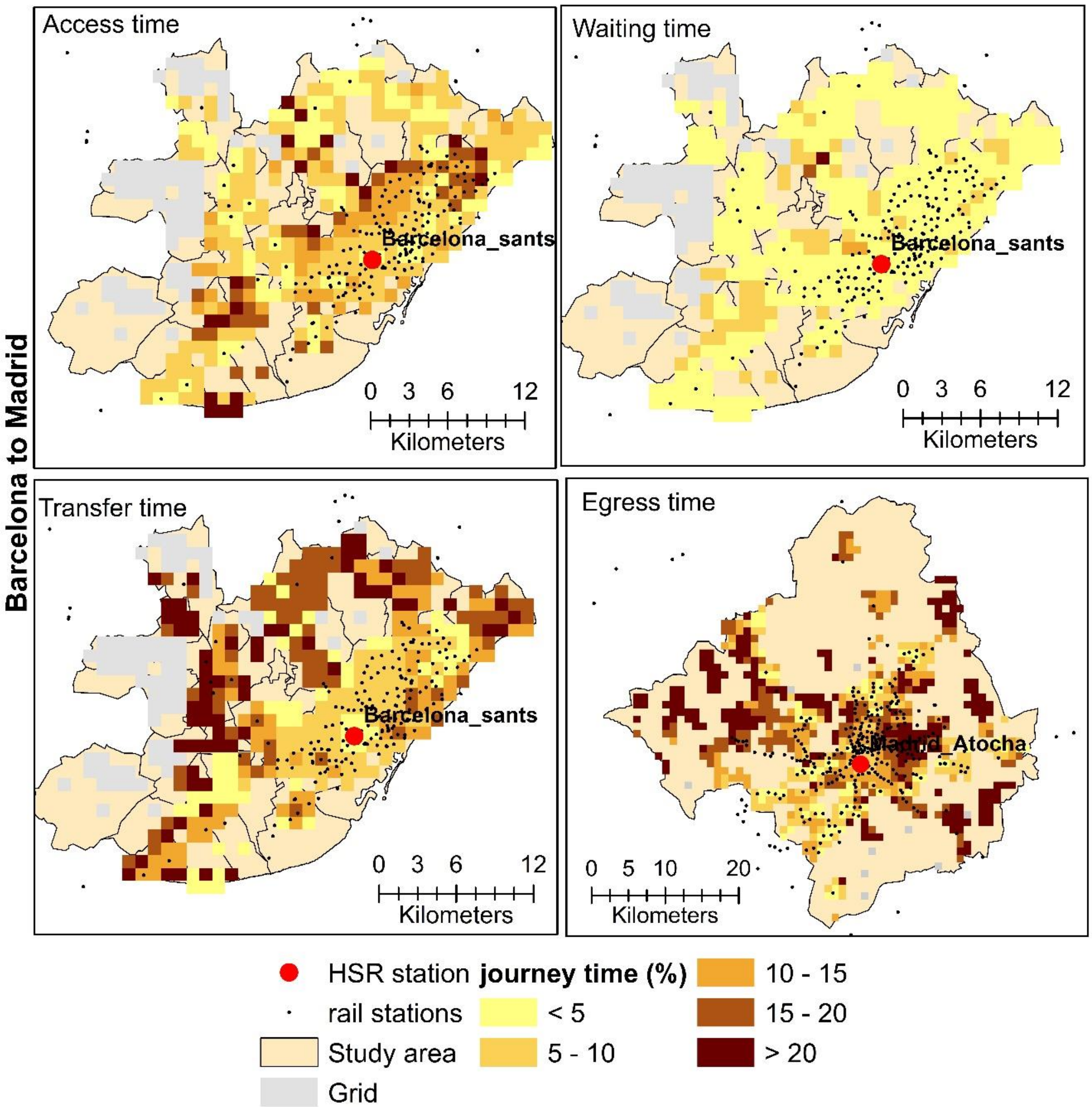


Figure 4.8 Spatial variation of access, egress, waiting and transfer contribution to D2D time in the Barcelona- Madrid corridor

### 4.5.3 Comparison and Summary

The provided analysis above delves into the quantitative investigation of each method, as outlined in the preceding sections. Moving forward, Figures 4.9 and 4.10 show the percentage point difference in the proportions of D2D journey time allocated to each segment in Barcelona-Marid and Hamburg-Berlin corridors. This comparison allows to identify the urban areas where the change in method has the biggest impact on results.

It is important to emphasise that Method 1 and Method 2 operate at different levels of disaggregation. In Method 1, the assessment encompasses access and egress time required for travelling to and from HSR stations, while in-vehicle time pertains to the duration of travel between these stations. Notably, Method 1 encompasses journeys undertaken via the local rail network within the access and egress phase. However, Method 2 takes a holistic approach by treating the railway network as an integrated system. Under this approach, all segments of the door-to-door journey involving any type of train, be it high-speed or local, are considered distinct components. As a result, the entirety of the rail journey is aggregated to derive the in-vehicle time spent between train stations, as well as the transfer time required between different trains. When considering the perspective of the travellers, the distinction between local and high-speed rail may not always be significant, the WebTAG data book assumes a same disutility value for all rail passengers, regardless of type of train service —be it conventional, regional, local, or high-speed trains. Consequently, aggregating all rail services within the same journey component can enhance readability and coherence in the assessment process. Moreover, the percentages of waiting time and transfer time are aggregated to facilitate a comparison with the waiting time percentage in Method 1. This aligns with the underlying assumption in this study that both waiting time and transfer time have equal disutility.

Given the dissimilar disaggregation of the methods, the percentage point difference allows us to comprehend how the two methods diverge in their treatment of journey components. It shows how much Method 1 differs from Method 2 in terms of the allocation of time to each segment. The calculation involves subtracting Method 2 values from Method 1. A positive difference indicates that Method 1 allocates more time to that segment compared to Method 2, while a negative difference means the opposite.

In Figure 4.9 for Barcelona-Madrid corridor, as anticipated, more zones experience that Method 1 assigns more time to access and egress phases compared to Method 2. This difference is particularly higher in the outer areas of urban regions. Conversely, Method 2 allocates more time to in-vehicle travel compared to Method 1, with the outer city areas showing a greater allocation of in-vehicle time for Method 2. In terms of waiting time, Method 2 allocates more time to waiting times across a large number of zones, except for the regions around the stations.

In Figure 4.10, focusing on the Hamburg-Berlin corridor, a similar pattern emerges. Once again, a greater number of zones indicate that the proportion of access and egress time is greater in Method 1 compared to Method 2. Notably, this trend is particularly pronounced in the southeastern part of Berlin, where HSR stations are situated further away. Method 1 allocates a higher proportion of time to egress in this region. Unlike Barcelona-Madrid corridor, in this corridor, the contribution of waiting time in Method 1 is greater than that in Method 2.

It is also important to compare the computation times of both methods. In Method 1, separate calculations for intra-city and inter-city journey times offer the advantage of reduced computation time due to smaller origin and destination matrices. For instance, in the Barcelona-Madrid corridor, the calculation involves origin-destination matrices of sizes 415 by 1 and 698 by 1, respectively. This approach typically takes around 1 hour to complete. However, Method 2 involves a more complex and time-consuming calculation. For instance, when calculating travel from Barcelona to Madrid utilising an origin-destination matrix of size 415 by 698, it took approximately 5 days and 6 hours to complete. Nevertheless, leveraging parallel computing operations can significantly reduce computation time. With a cluster comprising 30 computing nodes, each equipped with 40 CPUs (totalling 40 cores per node) and 64 GB of RAM, the computation time can be reduced to approximately 3 hours.

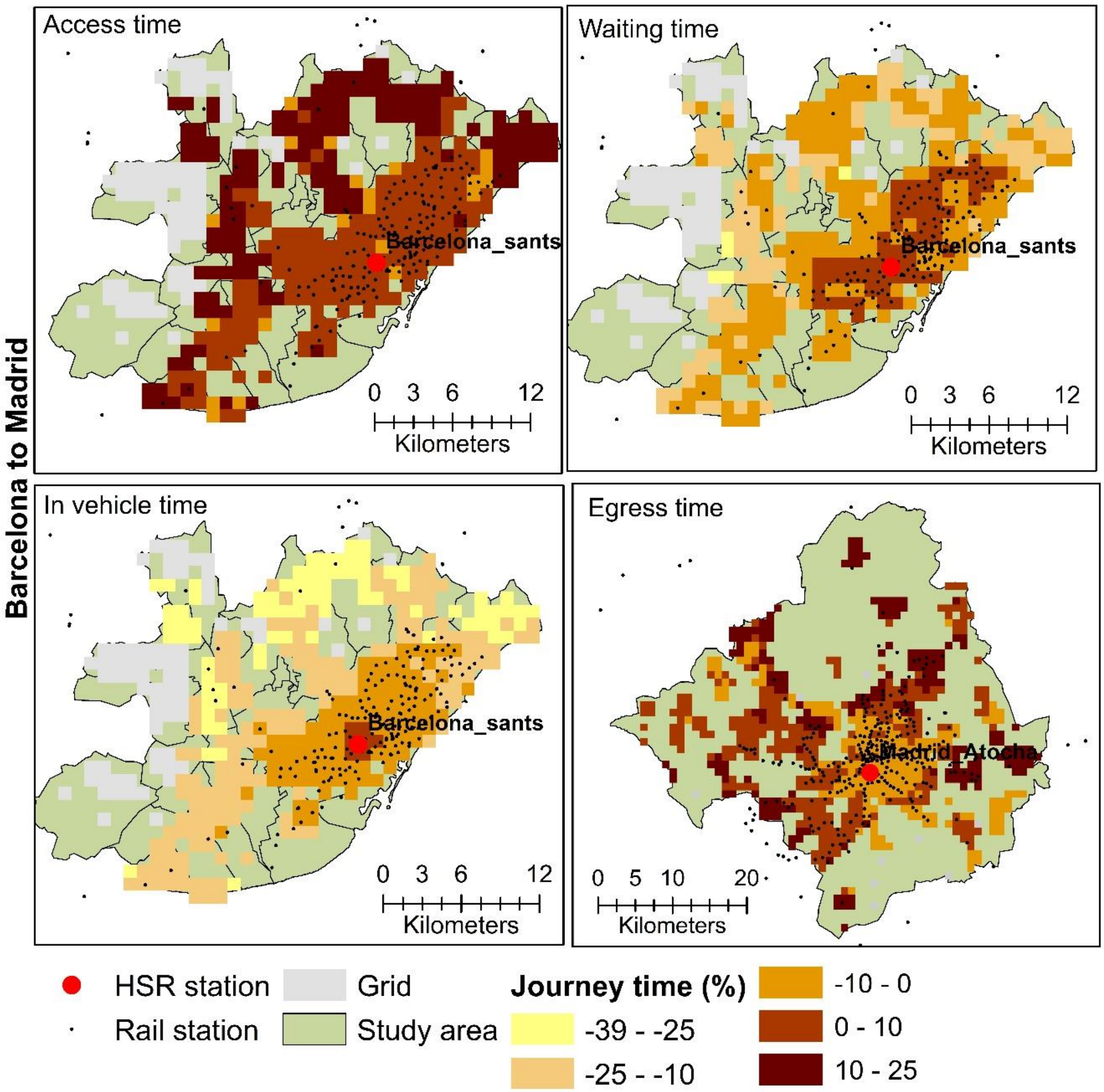


Figure 4.9 The percentage point difference between Method 1 and 2 for the Barcelona-Madrid corridor

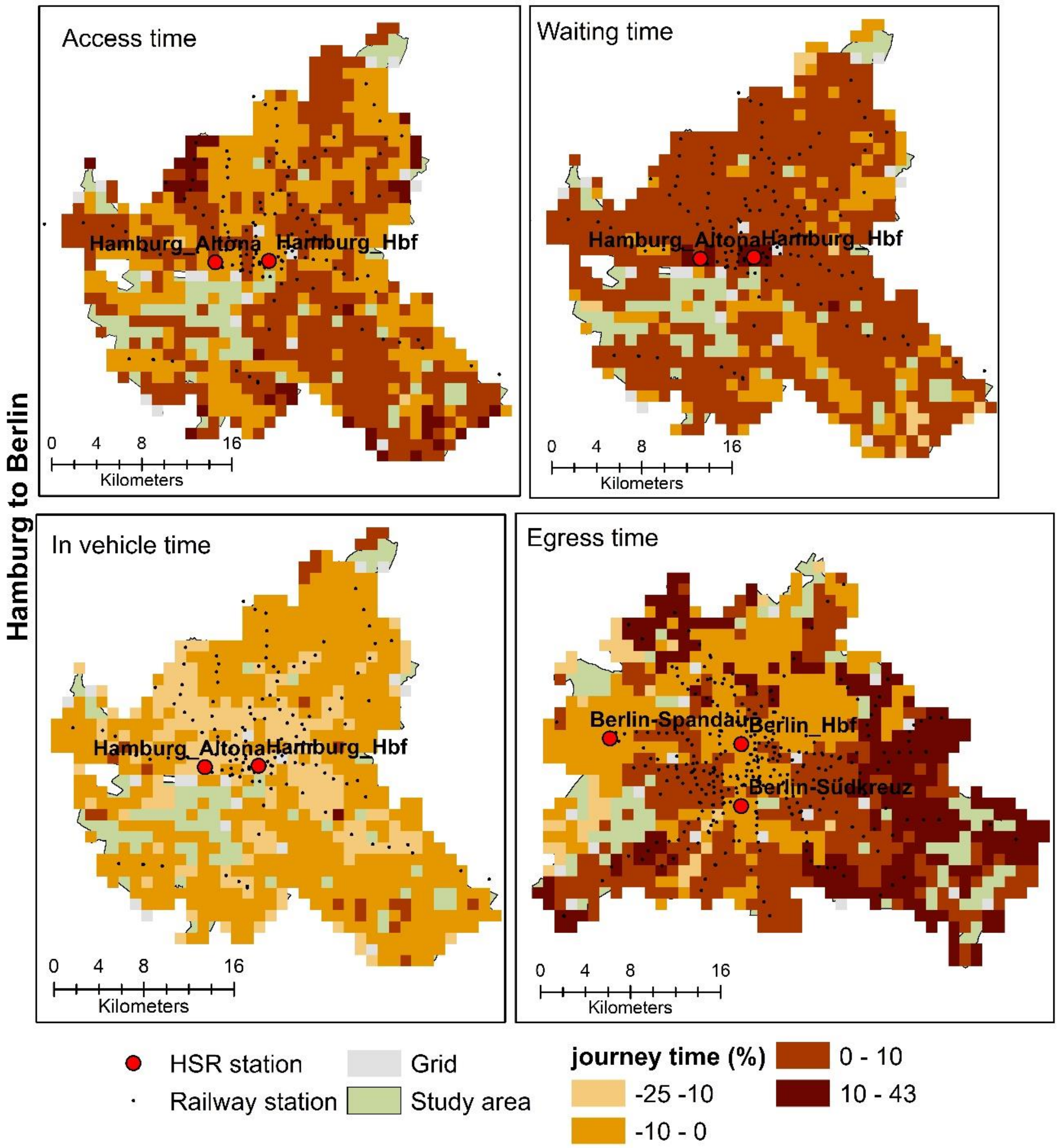


Figure 4.10 The percentage point difference between Method 1 and 2 for the Hamburg-Berlin corridor

This thesis employed Method 2 to offer a novel investigation into the factors impacting the overall accessibility of HSR. A comprehensive overview of both methods is as outlined below:

**Method 1**

Advantages:

- Performing separate calculations for intra-city and inter-city journey times can offer reduced computation time with a smaller number of origin and destination matrices.

Limitations:

- As each segment is treated independently, potential interactions between different transportation modes and the overall journey experience may not be adequately accounted for, leading to a less comprehensive understanding of the total travel time.
- Assuming the waiting time to be equal for all zones across the city is not realistic due to the inherent complexities and variations in transit modes and service irregularities.
- Calculating access/ egress times can become challenging and complicated in scenarios where multiple HSR stations exist within an area. The presence of multiple stations introduces complexities in determining the most optimal routes and travel options for passengers.

**Method 2**

Advantages:

- The holistic calculation approach can offer a more realistic estimation of travel times, as considering the integration level of journey stages and the impact of waiting and transfer time, as these factors may differ depending on the combination of transport modes used.
- The approach of separating journey components offers a high degree of flexibility, allowing the thesis to focus on specific aspects that align with its objectives.

Limitations:

- The approach assumes that users plan their journeys ahead and follow predefined criteria for selecting the optimal path. However, in reality, user preferences may vary, and some travellers might prefer more flexible journeys. This could lead to a discrepancy between the predicted and actual travel patterns.
- The process of calculating multi-modal paths and selecting the optimal path among various options can be computationally intensive, particularly when dealing with a large number of origin-destination matrices.

# Chapter 5 EXAMINING THE IMPACT OF HSR STATION LOCATION

## 5.1 Introduction

In a previous chapter of the thesis (Chapter 2), a literature review was conducted to find the studies examining the accessibility impact of HSR and to identify the factors that impact accessibility of HSR. The review found that good connectivity to the HSR network is a critical factor in achieving the benefits of HSR investment (Givoni and Banister, 2012; Monzón et al., 2016), and the connection between the HSR station and the local transport system is crucial for attracting passengers (Brons et al., 2009). The transportation solution for these connections depends on a wide range of factors, including: (1) the geographic location of the station; (2) the development of interconnected infrastructure for the transport system; and (3) the provision of integrated service management in terms of timetabling, service frequency, information, and fares.

The journey time advantage of HSR over conventional trains and other land transport modes is apparent for many corridors. However, previous studies have evaluated this benefit while thinking the station-to-station journey stage which is only one part of a door-to-door journey. Therefore, Chapter 3 of the thesis described the method used to analyse the accessibility impact of HSR, which considers the door-to-door journey time approach. This approach includes both intra and inter-city networks, which are essential for understanding the benefits of HSR investment fully. Then, Chapter 4 of the thesis tested the method using different HSR corridors and evaluated the importance and impact of different legs of journey by high-speed rail corridor on HSR accesibility level.

The current chapter, therefore, analyses and compares the accessibility benefits provided by different locations of the HSR station relative to the city by using the door-to-door journey time approach. The aim of this comparison is not to establish a definite judgment regarding the desirability of possible station locations, but it aims to fill in some gaps in existing methods of transport evaluation by emphasising the door-to-door journey time perspective. Indeed, the aim is to emphasise the importance of the inclusion of the door-to-door journey time approach into the evaluation process used to determine the location of HSR stations and infrastructure.

## 5.2 High-speed rail stations' location

The location of the high-speed rail station within the city that it serves can have a significant impact on the city's socioeconomic status. As Bertolini (1996) states, a train station plays two roles: it serves as an important nodal point in the transport network, while also functioning as a significant place within the city. Access to railway stations is an important component of door-to-door travel by rail, with studies examining the critical role of the city-station link. Accessibility to the station is a key factor that can influence whether a person chooses to use a train rather than a bus or a private car for travel (Cascetta et al., 2011). Proper integration of HSR stations within the urban area is therefore essential to fulfil their role as nodal points within the transport network.

The location of HSR stations within a local area can have a substantive impact on its development. A centrally-located station can take advantage of already existing complementary developments and serve as a catalyst for further development (Loukaitou-Sideris et al., 2012). In contrast, peripheral stations can attract economic growth around station and then contribute to urban decentralisation (Zhu et al., 2015). However, this type of urban planning approach should not be spontaneous urban spatial restructuring and is instead under the control of local authorities. Without appropriate control, the development around the station can lead to negative consequences such as urban sprawl, social and economic inequality (Kim and Yi, 2019).

Existing high-speed rail stations in Europe and Asia have been built either by converting existing stations to be compatible with the HSR network or by constructing new HSR stations, resulting in two distinct patterns of station placement. Upgraded HSR stations are typically located in densely populated urban areas, while newly constructed stations are more commonly found in the urban periphery, which refers to the outer edges of urban areas where there is less development and lower population density. However, there are exceptions to this pattern, as seen in the case of Birmingham Curzon Street station. In China, many stations are located in peripheral areas to decentralise cities (Wang et al., 2013).

While upgrading existing stations saves money on land acquisition, it severely restricts the alignment of HSR lines and causes operational difficulties during construction. On the other hand, peripheral HSR stations integrated with local transport can foster regional development while avoiding traffic congestion in the central city (Diao et al., 2017). However, the long distance between the HSR station and the city centre may reduce the benefit of inter-city travel obtained by HSR (Diao et al., 2017), thereby limiting frequent usage of HSR for business travel.

## 5.3 Railway station site selection

The choice of the location of a high-speed rail station is a critical decision that impacts its accessibility and overall accessibility in terms of the impact of HSR on door-to-door journey time. Many different criteria can be used to select a station site, including passenger demand, geometric, environmental, and economic constraints, the country's economic growth strategy and the existing built environment. Authorities make their plans by considering some or all these criteria. Some select the access time from the densely populated area to the station as a decision criterion (Chanta and Sangsawang, 2020), while other municipalities, such as those in China, have considered peripheral HSR station locations as a point of attraction for further city development towards the station, thereby decentralising cities (Diao et al., 2017).

HSR station can also act as hubs for the revitalisation of neglected areas (Mohino et al., 2014). For example, in the case of Lille Europe, the station's location in an area formerly dominated by heavy industry has helped to transform the area into a major transportation hub, with a mix of commercial and residential development (Liu and L'Hostis, 2014). Similarly, Stratford International station has played a vital role in the regeneration of the surrounding area in London in preparation for the 2012 Olympics. The original concept of HSR requires few stations along the line to be able to provide greater speed and shorter travel time; this situation increases the importance of station location.

Chanta and Sangsawang (2020) explain the procedure for determining railway station location in two stages. The first stage is to identify alternative solutions, in which various elements must be considered. These elements consist of the origin-destination flow, city structure, significant buildings, and transit links. After various solutions are identified, the second stage typically is to assess several alternatives and identify the optimum site. The accessibility considerations should be incorporated into assessment process, therefore decision-makers can more effectively evaluate the potential impacts of transportation projects on different populations and communities and make more informed decisions that prioritise accessibility and equity (Boisjoly and El-Geneidy, 2017). For example, Mateus, Ferreira and Carreira (2008) conducted a multicriteria analysis to evaluate six alternatives for the location of a railway station in the Porto metropolitan area in Portugal. Accessibility was measured in terms of travel time to the station, but the analysis was limited to representing only the time it takes to travel from the station to the city centre, without considering the spatial variation in accessibility across the city. However, to accurately reflect the impact of stations, it is necessary to have a more comprehensive and spatial assessment of accessibility. This would enable a more holistic understanding of the accessibility levels across the city, considering the location of destinations, the distribution of the population, and the quality of the transportation network.

Despite the previous studies on accessibility and high-speed rail, to the best of our knowledge, there is a lack of research on how the location of HSR stations relative to the city impacts accessibility and journey time benefits. While the construction of HSR can improve the accessibility level of connected cities, the location of the station relative to the city can affect the size of benefit gained. Therefore, this study aims to investigate how the different locations of HSR stations relative to the city centre can influence the accessibility benefits delivered by HSR to cities. By examining the impact of station location on accessibility, this study can help to identify optimal locations for HSR stations and inform future planning and development of high-speed rail networks.

## 5.4 Definition of case study (HS2)

High Speed 2 (HS2) is a planned high-speed railway network in the United Kingdom that will connect London, East Midlands, Birmingham, Manchester, and Leeds. The project was first proposed in 2009 to address capacity issues on the existing rail network and to provide faster, more reliable connections between major cities in the country.

HS2 will consist of two phases, see Figure 5.1. Phase 1 will connect London and Birmingham (221 kilometres) and is currently under construction. Phase 2 will extend the network to Manchester and Leeds (for a total of around 530 kilometres of high-speed train lines). Phase 2 is split in to two sub phases. Phase 2a will run from Birmingham to Crewe whilst Phase 2b will extend the route from Crewe to Manchester on the West Coast and the West Midlands to Leeds along the East Coast.

The UK government's Integrated Rail Plan (DfT, 2021), which was published on 18 November 2021, significantly altered the original proposal for the eastern leg of the HS2 programme. The new plan eliminates much of the eastern leg, leaving a branch from Birmingham to East Midlands Parkway station, just south of Nottingham and Derby. The plan also includes upgrades to the East Coast Main Line to improve travel times on the London to Leeds and Newcastle routes. HS2 trains will serve the centres of Nottingham and Derby, unlike in the previous proposal, see Figure 5.2.

Recently, on October 4, 2023, the Government unveiled 'Network North: Transforming British Transport,' a document outlining significant revisions to the HS2 project (DfT, 2023c). The key change involves the abandonment of Phase 2, resulting in the establishment of a new high-speed track from London to Handsacre, northeast of Birmingham, with a branch extending to central

Birmingham. This line connects to the West Coast Main Line at Handsacre Junction to allow HS2 trains to reach cities in the North of England and Scotland on the existing West Coast Main Line. The entire new HS2 line now consists of Phase 1, see Figure 5.1.

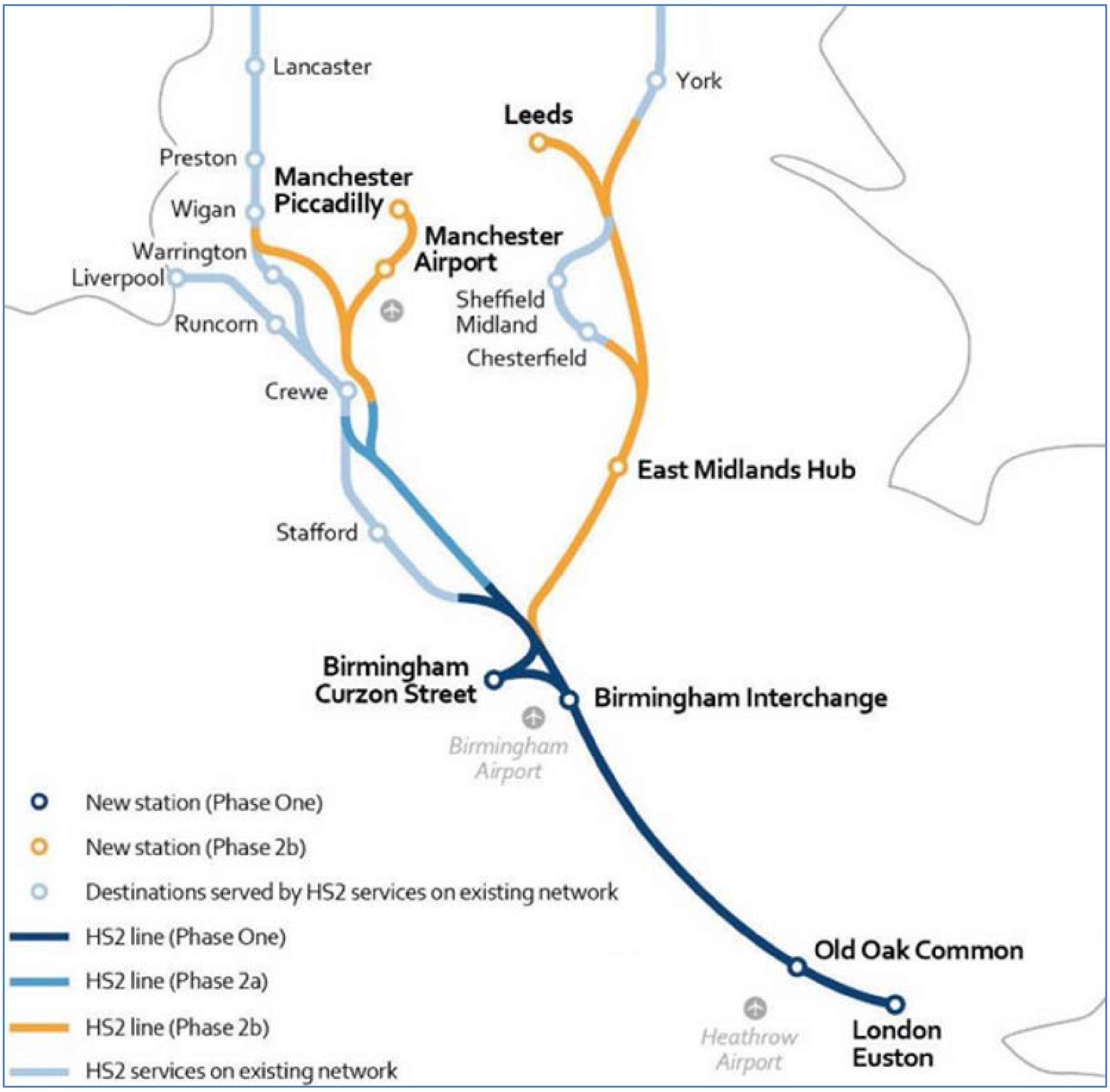


Figure 5.1 High speed two rail route map

*Source: (HS2.org.uk, 2023)*

While there are many high-speed rail corridors around the world that could serve as potential case studies, HS2 stands out for several reasons. One reason for choosing HS2 as a case study is its relevance to the research objectives. The substantive changes to the original proposal, particularly with regards to the eastern leg, make HS2 an interesting case study for understanding the impacts of station locations relative to the city on accessibility and travel time benefits. Another key consideration when selecting a case study for research is the availability and accessibility of data. In the case of HS2, publicly available data from various sources, including the UK government and transport agencies, can provide valuable insights into the planning, design, and operation of the project. Moreover, HS2 is a planned and partially under construction project, which allows us to evaluate the effectiveness of the planning and design process in achieving the desired outcomes, such as reducing travel times and increasing accessibility.

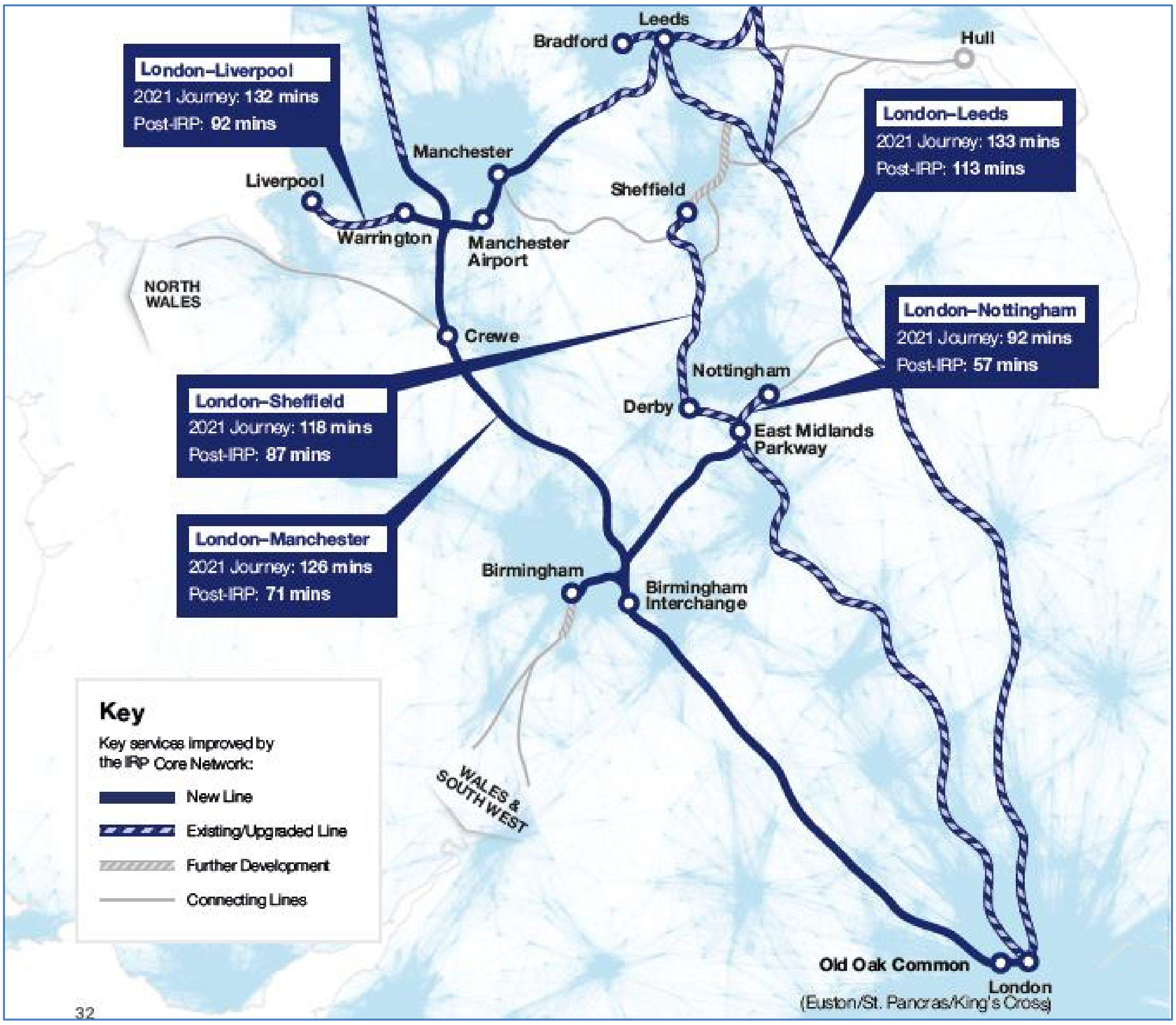


Figure 5.2 Integrated Rail Plan for High speed two rail route map

*Source: (DfT, 2021)*

## 5.5 Definition of scenarios

This study aims to empirically observe the impact of different station locations on the eastern leg of High Speed Two (HS2) Phase 2b, using it as a case study. Two planning approaches have been proposed for HS2 phase 2b, with the previous plan proposing the construction of a new HSR station located far from the city centres in the East Midlands (a peripheral area). In contrast, the new alternative plan involves integrating the high-speed train line with conventional lines to reach the city centres (DfT, 2021). These different design approaches coincide with the situation considered in this study, making the eastern leg of HS2 an ideal case study (See Figure 5.3).

Scenario 1 is the previous HS2 proposal with a new East Midlands Hub at Toton, while Scenario 2 represents the revised proposal with upgraded East Midlands Parkway, Derby, and Nottingham stations. However, for the purposes of this analysis, it has been assumed that high speed two services will not call at East Midlands Parkway. The study aims to compare the impact of different station locations (central and peripheral) on accessibility. In Scenario 1, the focus is on the development of a new East Midlands Hub at Toton, which is likely be a peripheral station for Derby and Nottingham city. Conversely, in Scenario 2, existing central stations are upgraded. The addition of stops at peripheral stations like East Midlands Parkway could diminish the overall efficiency and speed of the HS2 service, as each additional stop extends travel time. Excluding East Midlands Parkway from the HS2 route in Scenario 2 helps maintain consistency between the scenarios being compared and allows for a more direct comparison between central and peripheral station locations.

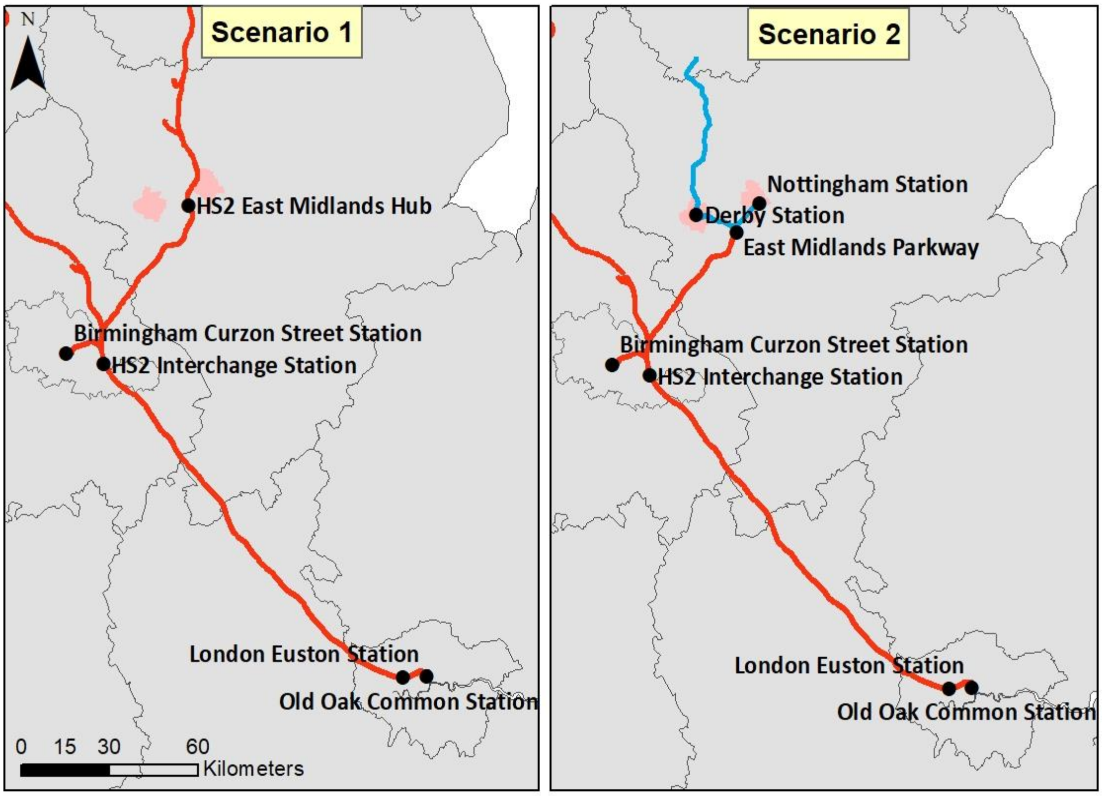


Figure 5.3 HS2 route scenarios

Scenario 1 was confirmed by the Government in its 2017 Phase 2b route announcement, which proposed a new East Midlands Hub station at Toton, approximately 8 miles west of Nottingham and 10 miles east of Derby. This peripheral station location was seen as an opportunity to increase inward investment, economic growth, and development. The plan included the establishment of a cutting-edge innovation campus that would bring together universities, start-ups, and established corporations (See Figure 5.4). The campus was intended to be a hub of technological innovation, generating up to 10,000 highly skilled employment opportunities and a network of adjacent garden communities (Midlandsconnect.uk, 2020). Nottingham City Council supported the East Midlands Hub Plan plans, whilst Derby City Council preferred the station to be located at the existing Derby railway station site (East Midlands HS2 Growth Strategy, 2017).

In November 2021, the UK Government released a new plan for rail transportation in the North and Midlands (DfT, 2021), which changed the previous HS2 plans. Under the revised plan, HS2 will be constructed from the West Midlands to the existing East Midlands Parkway station, using the same route and line speed as previously intended. East Midlands Parkway is located about six miles southwest of Nottingham, and around three miles from the previously proposed East Midlands Hub at Toton. From East Midlands Parkway, HS2 trains will run directly to Nottingham, Derby, Chesterfield, and Sheffield on the upgraded Midland Main Line. This is a substantive change from the previous plan, as HS2 will now serve Nottingham and Derby city centres, rather than being located far away in a peripheral area. The new plan is expected to reduce travel time from London to Nottingham to just 57 minutes. The station-to-station travel time between London and East Midlands Hub is 52 minutes but reaching the city centre of Nottingham and Derby requires changing trains at East Midlands Hub. The integration of HS2 trains with the existing regional public transport networks in Nottingham and Derby will also improve local rail services (DfT, 2021).


Figure 5.4 Current view of Toton area and proposed development layout

*Source: (East Midlands HS2 Growth Strategy, 2017)*

### 5.5.1 Station integration with local public transport

Station integration with the local transport system is a crucial part of the proposed developments. Local and long-distance services should be planned together, rather than separately. In this study, we do not consider the further development of existing stations in Scenario 2, as they are already active and well connected to the local public transport system. In contrast, the peripheral location of new East Midlands Hub at Toton in Scenario 1 would require investments in local transport networks to serve the site, including the rerouting of the East Midlands rail and other public transport networks to station. Figure 5.5 shows the relative location of the East Midlands Hub to Derby and Nottingham. Therefore, the East Midlands city and county councils have developed a future plan for access to Toton, consisting of three phases to be implemented and operational within 10, 20, and 25 years (Midlandsconnect.uk, 2020). This study only considers the development within 10 years (Phase 1) to be able to see the immediate impact of HS2 upon opening. Figure 5.6 shows a map of how the planned network would have been integrated with East Midlands Hub station.

Phase 1 includes 5 stages (East Midlands HS2 Growth Strategy, 2017): (1) The extension of the Nottingham tram system from the Toton Lane Park and Ride site to Long Eaton via two new stops at the planned innovation campus development and HS2 East Midlands Hub station; (2) New bus services between the HS2 East Midlands Hub and Amber Valley, West Bridgford and Clifton. (3) Bus rapid transit between the HS2 East Midlands Hub station and Derby city centre via Pride Park and Derby railway station; (4) Revision of the current local bus network as proposed in the East Midlands HS2 growth strategy plan; (5) The implementation of a minimum of four direct rail services per hour linking the HS2 East Midlands Hub station to Derby, Nottingham, and Leicester stations, as well as Loughborough, Matlock, Mansfield, Newark, Alfreton and Grantham. (6) New rail service between Mansfield, Derby and Leicester with stops at Ilkeston, Langley Mill, Kirkby in Ashfield, Sutton Parkway and HS2 East Midlands Hub.

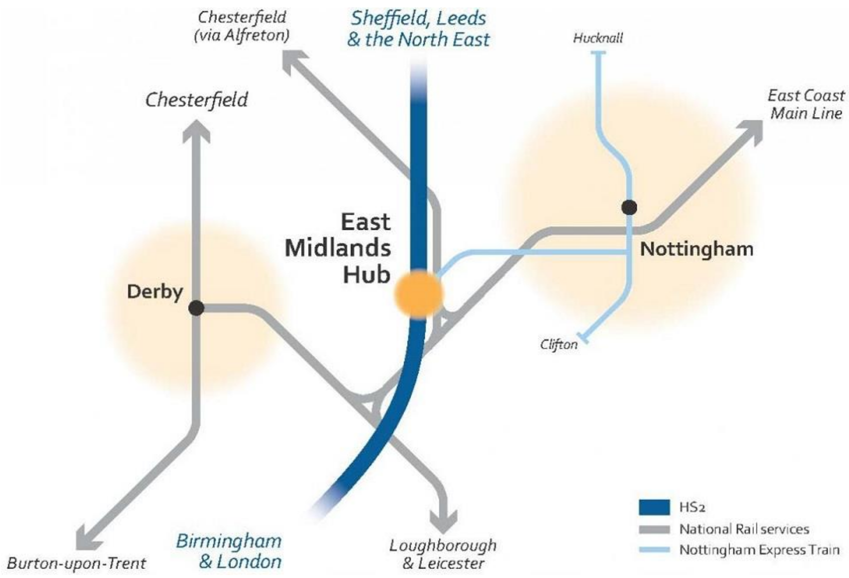


Figure 5.5 The relative location of East Midlands Hub to Derby and Nottingham

*Source : https://www.gov.uk/government/publications/east-midlands-hub*

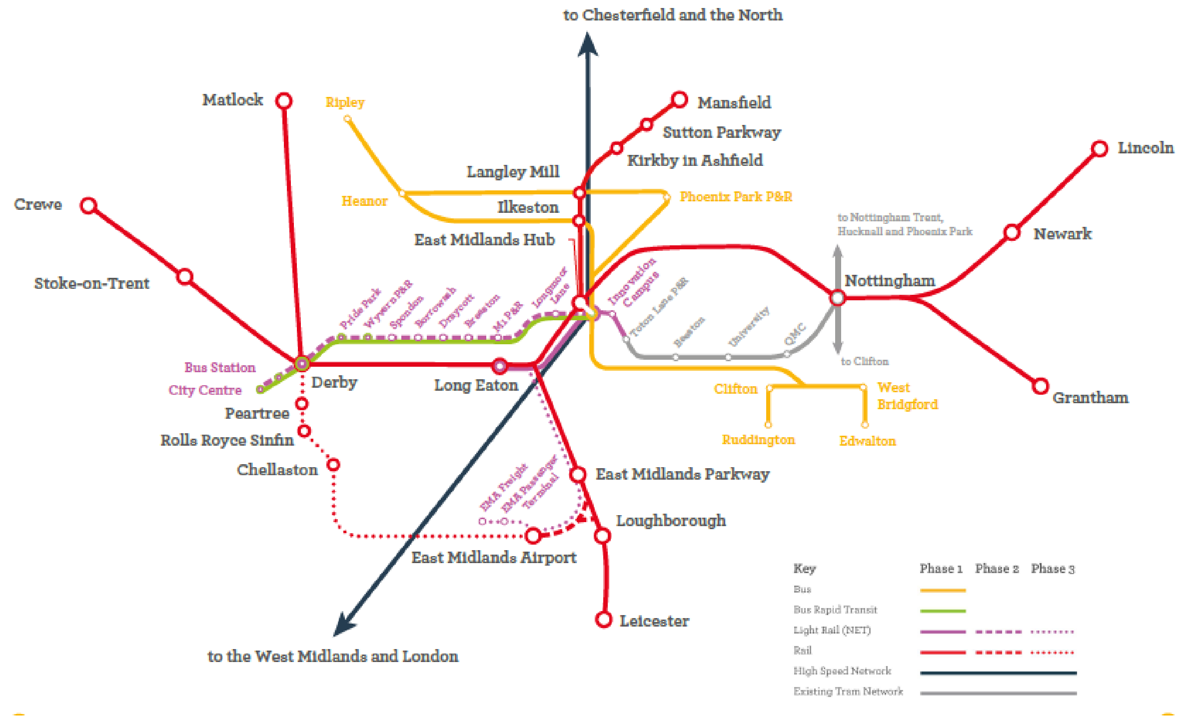


Figure 5.6 Integrated transport map to access to East Midlands Hub

*Source: (Midlandsconnect.uk, 2020)*

## 5.6 Data Preparation

The task of creating a multi-modal public transport model can determine the best routes between thousands of origins and destination points while precisely measuring the duration of each journey stage (including access, waiting, and in-vehicle journey). The multi modal network requires spatial data for street networks and timetable data for public transport systems. Detailed street network data is available through OpenStreetMap, which is open-source mapping that provides free and editable geographic data to users all over the world (Openstreetmap, 2022). It is often referred to as the "Wikipedia of Maps" because anyone can contribute to it by adding and editing features such as roads, buildings, and points of interest.

GTFS data containing information about public transport timetables and station locations is increasingly becoming available. The introduction of online journey planners and the development of Google's GTFS have helped to standardise transit data internationally and encouraged city authorities to release public transport data (Google, 2016). GTFS data is crucial for modelling public transport travel times, as it includes key information such as transit station location geography and timetable data with service frequency. Therefore, three different timetable datasets in GTFS format were used: local public transport timetable (buses, tram, metro), regional and intercity conventional railway timetable, and high-speed railway timetable.

GTFS data from the official website[8] were used to obtain local public transport service information. August 2022 was chosen as the date for obtaining GTFS data for local public transport services because it was recent and up to date, making the analysis more accurate. GTFS data for regional and intercity conventional railways were obtained from transitfeeds.com[9] in April 2021. However, this dataset probably shows reduced service levels due to the Covid lockdowns, and therefore might not present a very accurate picture for our research. The most recent available pre-pandemic data was October 2019 on that website, so it was selected.

To ensure consistency in the analysis, timetable data for all public transport services must be for the same date range. The calendar date for conventional trains was therefore, manually adjusted from 2019 to 2022. The new GTFS file was compared to the Google Maps for accuracy. A few origin and destination examples were selected to perform the comparison and then both GTFS and Google Maps were used to generate transit journey options. It has been essentially checked how closely the information provided by GTFS matches with the information provided by Google Maps for the same OD pairs. This process involves comparing the routing information, trip schedules, and other details related to the transit journey, and found that there are no substantial differences.

As mentioned in section 5.5.1, there are new rail and local public transit services for the scenario 2. Schedules for the new services need be prepared in GTFS format, which includes timetables, routes, trips, and the coordinate of stops. The indicative estimates of the frequencies and journey times of these services are provided by in the Access to Toton document (Midlandsconnect.uk, 2020). For Bus rapid transit between the HS2 East Midlands Hub station and Derby city centre, it is assumed that new services operate between 06:00 to 23:59 hours each day. The route is decided based on the map provided in Figure 5.6. based on a plausible service pattern which fits into the existing timetables.

GTFS data of HS2 corridor was created following the proposed route, stations and scheme service pattern in the official document (DfT, 2017). According to this report, HS2 will operate between 05:00 to 23:59 hours Monday to Saturday and 08:00 to 23:59 hours on Sundays. These would be the times between the first train of the day setting off from its origin to the last train completing its journey. The services would operate three train services per hour from London to Birmingham, Manchester, and Leeds, with intermediate stops along the way. The planned journey time

[8] Accesibile at: https://data.bus-data.dft.gov.uk/timetable/download/
[9] Accesibile at: https://transitfeeds.com/p/association-of-train-operating-companies/284

between stations is obtained from the official website (HS2.org.uk, 2022), See Table 5.1. Figure 5.7 shows the proposed hourly service pattern for the HS2 route (DfT, 2017).

Table 5.1 Estimated journey times from station to station for scenarios

| | Estimated journey times between stations in minutes | | |
|---|---|---|---|
| | Do nothing | Scenario 1 | Scenario 2 |
| London - Nottingham | 92 | 83 | 57 |
| London - Derby | 86 | 83 | 58 |
| London - Sheffield | 136 | 79 | 87 |
| London-Birmingham | 80 | 45 | 45 |
| Birmingham - Nottingham | 74 | 55 | 26 |
| Birmingham - Derby | 34 | 30 | 30 |

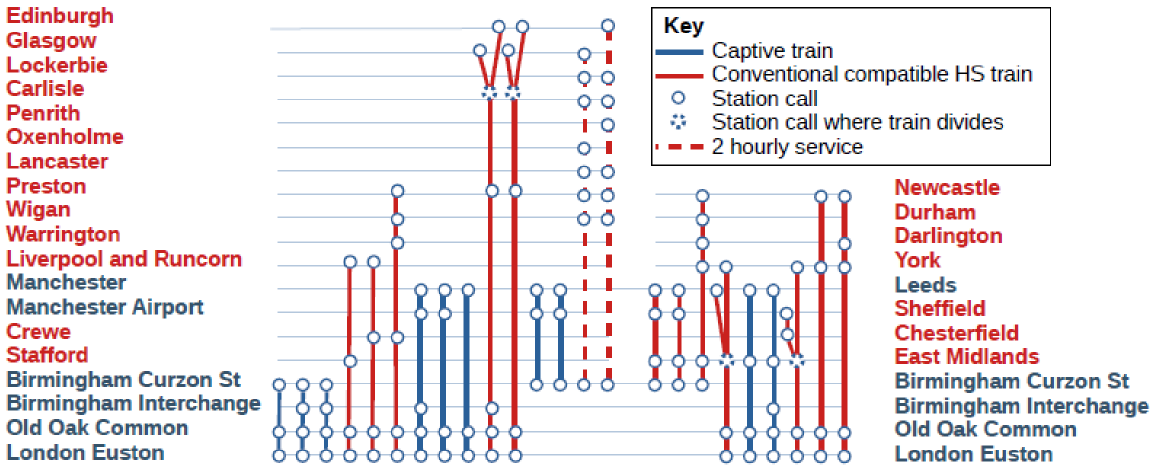


Figure 5.7 Hourly service pattern for HS2 route

*Source: (DfT, 2017)*

This research primarily focuses on door-to-door travel time, so it is increasingly important to consider the number of origins and destinations across cities. If the origins and destinations are only represented by a few points, such as major transportation hubs or city centres, the estimated journey time may not account for the time it takes to travel from a person's home or workplace to the nearest transportation hub or city centre. This could result in an underestimation of the total journey time. On the other hand, if the origins and destinations are represented by a large number of points, such as individual households or businesses, the estimated journey time may be more accurate and account for variations in travel time caused by factors such as traffic congestion, road conditions, and public transportation schedules. Therefore, it is important to include a sufficient number of origins and destinations representing cities when calculating the journey time. The sufficient number depends on several factors such as the mode of transportation, the size and complexity of the cities, and the level of detail required in the analysis.

There are several methods and data sources that can be used to identify origins and destinations. First is to conduct a household survey that asks people about their travel patterns (Chen et al., 2016). This can provide detailed information about where people start their journeys, the modes of transportation they use, and the purpose of their trips. Second is to use mobile phone data, which can provide information about people's locations and movements in real time (Moyano et al., 2018). This can be useful for understanding patterns of travel across different parts of the city, and for identifying areas where people tend to start their journeys. Third option is to use GPS tracking devices to collect data on the movements of individuals or vehicles (Carrion and Levinson, 2019). Finally, census data, which provides information on the demographic characteristics of households and individuals in different geographic areas (Mavoa et al., 2012). By analysing census data, it is possible to identify areas with high populations of potential origin points, such as residential neighbourhoods or business districts.

This study used census data due to its advantages over other data sources. It covers a large sample of the population in each geographic area, is designed to be representative of the population as a whole, and publicly available. In the UK, census data is collected at several different geographic levels. The smallest geographic unit used is called an Output Area (OA), which typically contains around 125 households or 300 people. OAs are then grouped together to form Lower Layer Super Output Areas (LSOAs), of which there are approximately 32,000 in England and Wales. LSOAs typically contain between 1,000 and 3,000 people. LSOAs are then grouped together to form Middle Layer Super Output Areas (MSOAs), of which there are approximately 7,200 in England and Wales. MSOAs typically contain between 5,000 and 15,000 people. (ONS, 2011). A comparative calculation has been made to determine the differences among these levels to choose for our study.

West Midlands has been used for the comparison. Access time via public transportation from origins across West Midlands to New Street rail station was calculated. Centroids are population-weighted geographical centres of different levels of zones and are used as origin and destination points in journey time calculations. In the West Midlands, there are a total of 8,728 OAs, 1,718 LSOAs, and 358 MSOAs, see Figure 5.8. The number of origins in OAs is comparatively higher than LSOAs and MSOAs. A geographic level that is more detailed would be better to observe the change of access time to different station locations. This would provide access time variations within smaller areas and identify patterns that may not be apparent at a larger scale. However, more origins mean the more calculation durations. The line graph (Figure 5.9) shows the number of origins within each access times to New Street station according to three geographic zones. The distribution of origins could have an impact on the average journey time calculation, as areas with a higher concentration of origins may skew the results compared to areas with fewer origins.

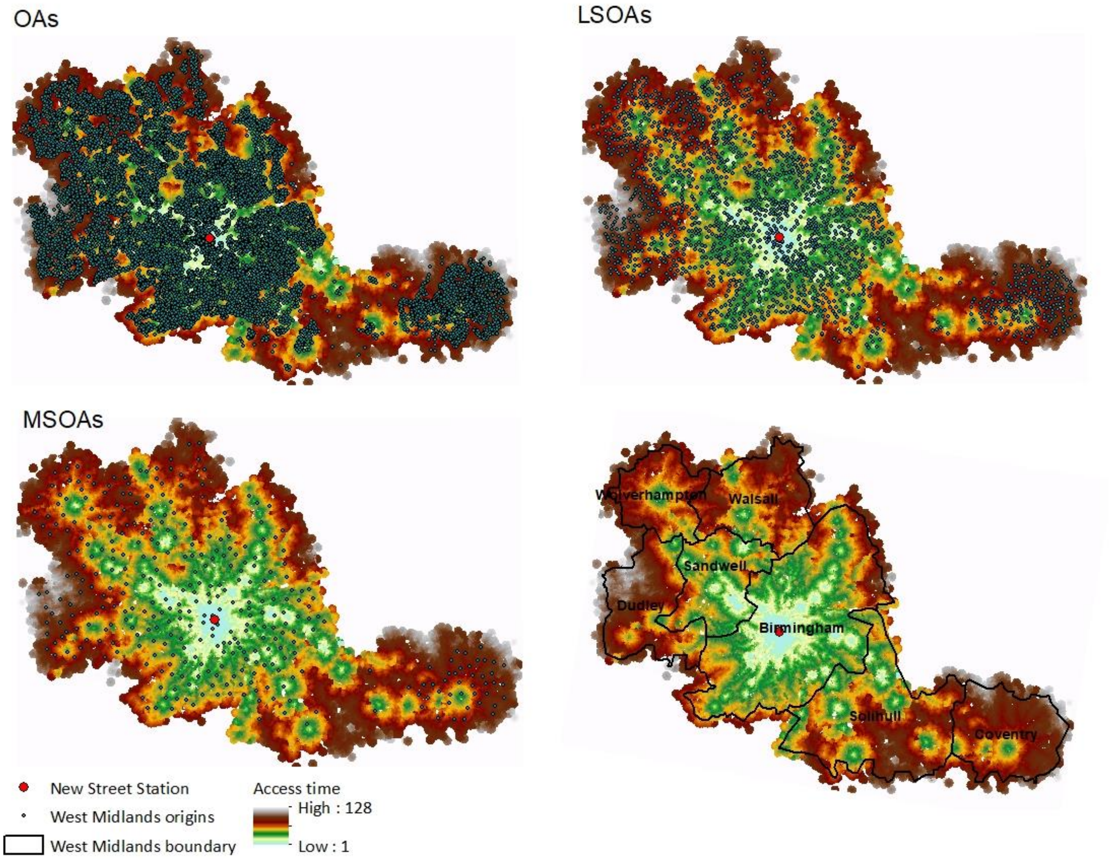


Figure 5.8 Spatial distribution of origins in accordance with different geographic zones

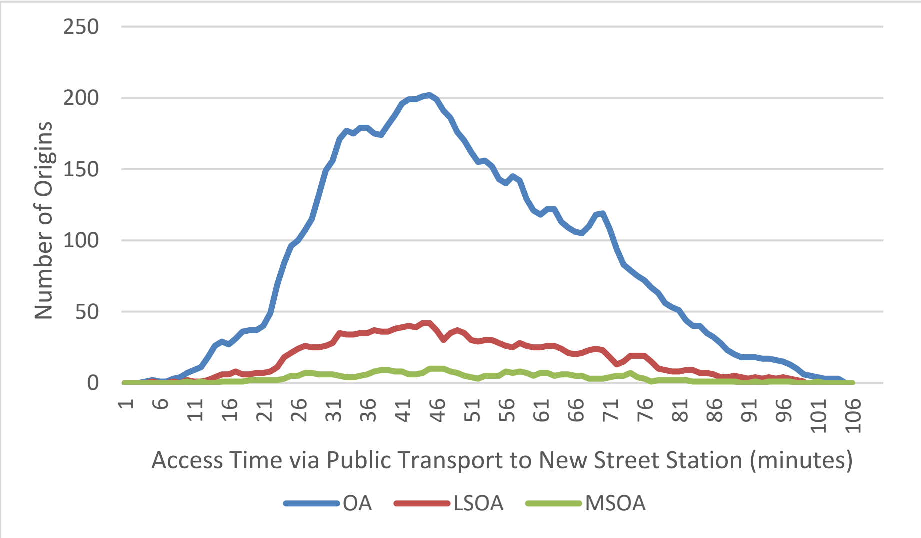


Figure 5.9 Temporal distribution of origins in accordance with different geographic zones

The line graph (Figure 5.10) shows the number of people living within different access times to Birmingham station according to three geographic zones. The population within each access time varies significantly between the different geographic zones. It is interesting to note that OAs and LSOAs show a similar pattern to MSOA in terms of the number of people living within different access times to Birmingham station. In general, the population within each access time is highest for MSOAs, followed by LSOAs and then OAs. This is likely due to the larger size and population of MSOAs compared to LSOAs and OAs. Based on all these observations, to ensure both computational efficiency and accurate geographic representation, the analysis was conducted at the level of Lower Layer Super Output Areas (LSOAs).

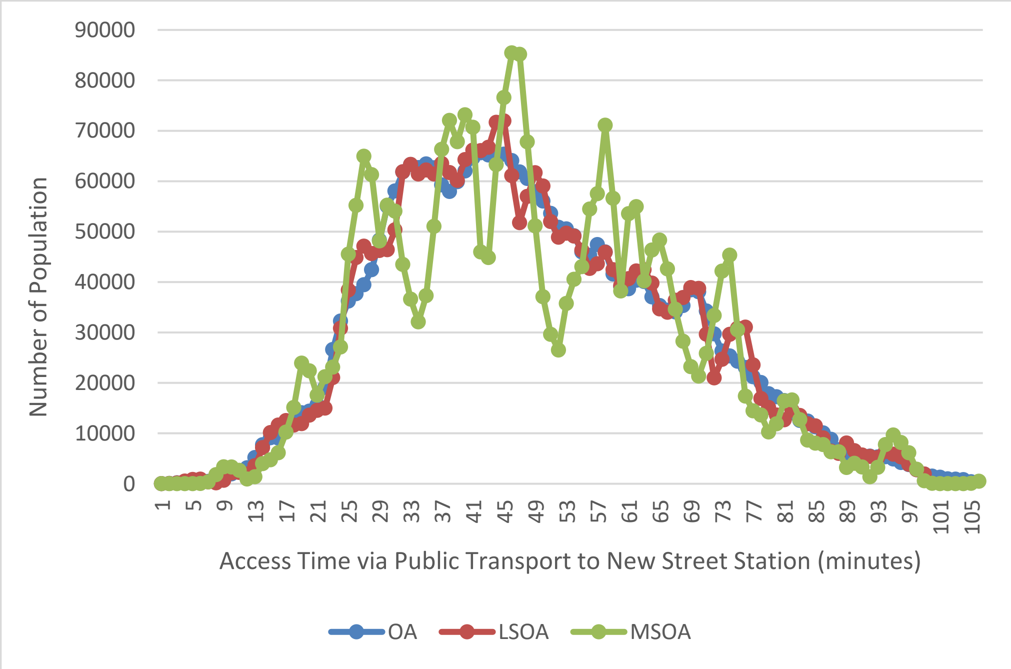


Figure 5.10 Population distribution depending on the geographic zone and access time

## 5.7 Intercity accessibility

High-speed rail development has the potential to enhance accessibility between connected cities, but the effectiveness of this improvement can be influenced by the strategic positioning of HSR stations within these cities. Existing evaluations of accessibility in HSR systems have primarily concentrated on the travel time between cities, neglecting the additional factor of the time it takes for passengers to travel within the city to reach the HSR stations. This section will examine the answer of: How does the accessibility of the city change according to the location of the stations to the urban area?

### 5.7.1 Service area delimitation

The initial stage of evaluating alternative transport plans or scenarios usually involves demand forecasting procedures, which are important for calculating the costs and benefits of the proposed transport system. Demand forecast models firstly must define the service area for a rail station. Many factors are considered to identify potential rail users such as the proximity of station location to urban area (Martínez et al., 2016) and competition with other stations (Givoni and Rietveld, 2014), the level and quality of train services offered at each station (Brons et al., 2009), the distance and direction of passengers' train trips (Young and Blainey, 2016), and the availability of other transport modes at the station (Brons et al., 2009).

In the literature, defining the service area for a rail station in a demand model typically involves several methods. One common approach is to create a buffer zone around the station based on a specific distance or time threshold (Marti-Henneberg, 2015b). The size of the buffer zone can vary depending on the context and characteristics of the rail station. For example, a buffer zone of 10 km or 30 minutes' travel time could be defined around the station, and all locations falling within this buffer zone are considered part of the service area for that station.

Another approach for defining the service area boundary is to use the administrative boundary of the surrounding urban area (Romero et al., 2021). This method assumes that the rail station serves the population within the administrative boundary of the urban area. Using administrative boundaries as the service area boundary offers a standardised and easily identifiable definition for analysis and planning purposes. It allows for consistent comparisons and assessments across different stations and areas within the region, ensuring a comprehensive understanding of the rail network's impact and potential user base. However, it may oversimplify the catchment area, as administrative boundaries are not specifically designed for transportation planning and may not accurately reflect travel patterns.

Another method for determining the service area and identifying potential users is to assign individuals to the nearest station across the region (Blainey, 2010). This approach assumes that passengers tend to choose the nearest station available to them, simplifying the definition of the service area by considering the proximity of the station to potential users. This method is simple to implement and provides a realistic representation of travel patterns. However, it has limitations, as it assumes that individuals always choose the nearest station, overlooking variations in travel preferences and neglecting other important factors such as transit network characteristics.

Recently, probabilistic station catchments have been developed as an improved method (Young and Blainey, 2018). This approach predicts the probability of a station being chosen from a set of alternative stations, considering the patterns of attraction and competition between railway stations. Probabilistic station catchments are useful for identifying potential users at stations in cities where there is more than one station or where a new station has been introduced. This method allows for a more sensitive and dynamic representation of the service area based on the probabilities of station choice by potential users.

Although this enhanced method may provide a more accurate and flexible definition of potential service areas, it does not serve the purpose of our study, which is to compare the locations of stations relative to cities. To conduct a comparative analysis, it is important to keep certain factors constant to ensure a consistent and meaningful comparison, including defining the service area for different stations as the same. However, the probabilistic station catchment method is dynamic and can be impacted by the presence and absence of a station.

The service boundary shown in Figure 5.11 is selected as study area. There are 616 origin centroids within the boundary. The chosen boundary includes the city centre areas of Derby and Nottingham, as well as the zones between the two city centres. The city centre areas are important transportation hubs and economic centres. The zones between the city centres of Derby and Nottingham are expected to be areas that will benefit from improved accessibility due to the introduction of HSR. These areas are likely to experience changes in travel patterns and economic development opportunities because of the HSR, making them relevant areas to include in the study boundary. The boundary also includes areas with higher population density, as these areas are likely to have more potential users of the HSR system. As a result, the chosen boundary likely represents a practical and manageable area for conducting the comparative analysis of different station locations. It allows for a consistent and focused analysis, reducing the complexity of including a larger area while still capturing the areas that are most directly affected by HSR design options.

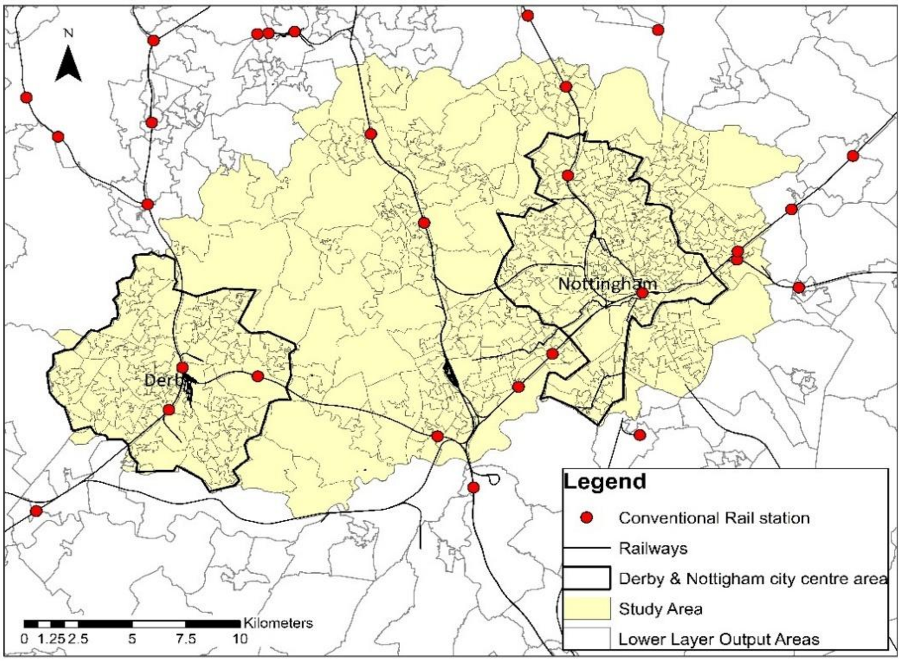


Figure 5.11 Case Study Boundary

West Midlands County and Greater London are selected as destination regions to evaluate how different scenarios impact the accessibility of studied region to other areas (Figure 5.12). These destination regions are represented at the level of Lower Layer Super Output Areas (LSOAs), as similar for origin region. West Midlands County comprises 1,718 destination centroids, while Greater London consists of 4,985 destination centroids across the region. Therefore, the journey time is computed from each of the 616 origins in East Midlands to all 1,718 destinations in West Midlands, and to all 4,985 destinations in Greater London, in order to reach the same destination centroids from all origin zones. Subsequently, the average journey time is calculated based on these computations.

Figure 5.12 Destination city boundary and centroids


Figure 5.13 Destination city boundary and centroids

### 5.7.2 Spatial distribution of employment and population

The distributions of employment and population describe the distributions of possible passengers from three sorts of journeys, namely business, commute, and leisure trips. Business and commuting journeys are usually made by individuals with jobs, whereas leisure trips are open to everyone. This differentiation in the demographics of passengers helps in comprehending the diverse trends in travel and the demand for different trip objectives. The spatial distribution of employment significantly influences business and commuting trips, whereas the spatial distribution of the population directly affects leisure trips.

The 2021 Census offers comprehensive data on various population characteristics and subject areas, including details like the count of usual residents in households and their economic activity statuses (Office for National Statistics, 2023). The population considered in this analysis is based on the number of usual residents in households. The employment is based on the individuals who are aged 16 years and over and are considered economically active if they are employed.

It's important to note that there are two types of employment data: employment by residence and employment by workplace. Employment by residence refers to the number of individuals employed in a specific area based on their residential location, while employment by workplace represents the number of individuals employed in an area based on their workplace location. For this analysis, we focus on employment by residence data. This decision is made because the zoning systems used to categorise employment by workplace do not align with the population dataset utilised in this study. Consequently, integrating employment by workplace data would pose notable challenges in terms of harmonising and interpreting the datasets effectively.

Figure 5.13 shows how population and employment is spread across the case study area. A higher population density is indicated with darker colours, and the same goes for employment distribution. A noteworthy observation emerges within the boundaries of Nottingham city centre. Despite the area exhibiting a high density of population, it displays a low distribution of employment. Derby centre has visible correlations between the population and employment distributions, areas with a high population density have high employment density, and correspondingly, low-density areas have less employment.

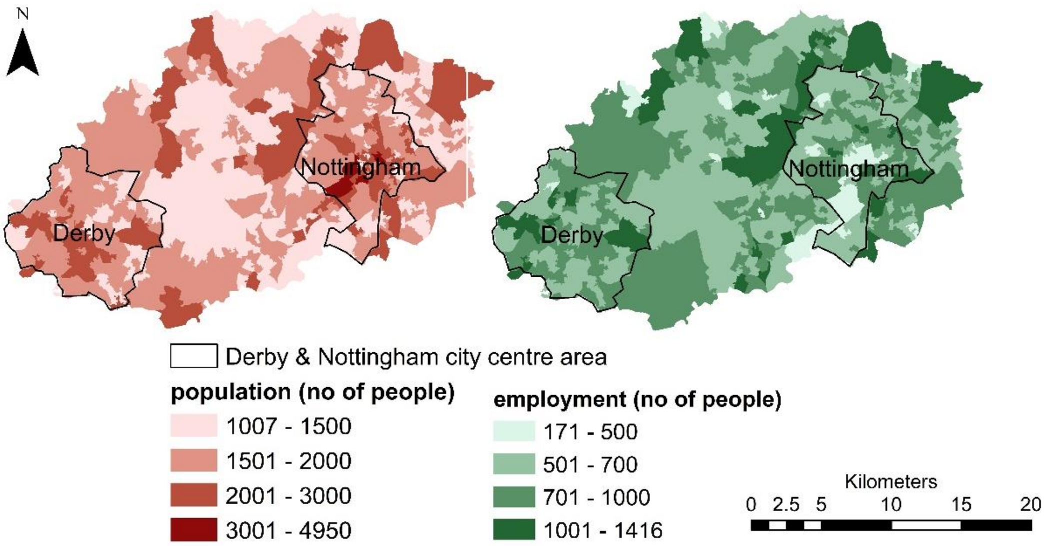


Figure 5.14 Population and employment distribution

### 5.7.3 Results

#### 5.7.3.1 Door-to-door journey time change

This section presents the results of scenarios regarding different HSR station locations. The change in accessibility of the case study area to London and West Midlands is evaluated based on two different scenarios. The study area (East Midlands) comprises 616 zones (origins), while Greater London and West Midlands as destination regions have 4,985 and 1,718 zones respectively. Constructing the HS2 project in either scenario 1 or scenario 2 can generate substantial gains in accessibility. However, the extent of these enhancements varies across different geographical areas. This variation is attributed to differences in station locations and service frequencies between the scenarios. It is expected that peripheral stations, such as Toton in Scenario 1, would typically operate with higher train frequencies compared to central stations located on different branches, such as Derby and Nottingham in Scenario 2. This expectation is rooted in the broader dynamics of transportation planning, which prioritise higher frequencies at peripheral stations to accommodate larger catchment areas and facilitate seamless transfers.

To find the spatial variation, journey times are computed from each of the origins in East Midlands to all destinations in West Midlands and Greater London, in order to reach the same destination centroids from all origin zones. The station-to-station journey time from East Midlands to London is almost double the time to West Midlands, so an individual review of each corridor will help to observe the effect of design options with different distances. The spatial variation of total change in journey time (minutes), under the two HSR scenarios, to two specific regions: Greater London and West Midlands is presented below.

Passengers can reach their destination cities via the HSR line if it provides a shorter travel time, resulting in enhanced accessibility. Alternatively, they can still use the conventional network, maintaining the same travel time as before. Among the zones, the yellow areas exhibit the least improvement in accessibility due to the HSR construction. Consequently, passengers in these zones might favour taking a conventional train over an HSR train. On the other hand, the blue zones experience the most significant accessibility benefits from this new system, whereas the green zones enjoy moderate advantages.

#### 5.7.3.1.1 To Greater London

In the base scenario, the station-to-station journey times from Derby and Nottingham to London (St Pancras station) are approximately and 87 and 102 minutes. However, the scenario 2 is expected to reduce travel time from London to Derby and Nottingham to just 57 minutes. In scenario 1, the station-to-station travel time between London and East Midlands Hub is 52 minutes but reaching the city centre of Nottingham and Derby requires changing trains at East Midlands Hub. Figure 5.14 explicitly visualise the spatial distribution of the change in total journey time to London between the base case and proposed scenarios.

In scenario 1, the northern area of the new East Midlands hub appears as a clear winner with substantial improvement. However, the southern part of the station exhibits much less improvement. This discrepancy can be attributed to the presence of a direct service from the conventional train station (Long Eaton) to London in the base scenario. Notably, the total journey time has been significantly reduced by up to 118 minutes in extreme cases (Figure 5.14). As anticipated, significant improvements are concentrated in the peripheral areas rather than the city centres of Derby and Nottingham. The improvement in Derby city centre zones is comparatively lower than that in Nottingham centre zones. This disparity could be perhaps because the planned new local transportation network is not sufficient to enhance the benefits to these regions.

Scenario 2 is the most recent plan for the HS2 route. Nottingham city centre and surrounding areas would benefit most from this scenario. Notably, in the most extreme case, the total travel time to London has been reduced by 92 minutes. Interestingly, there is a disparity in accessibility improvement between Derby city centre and Nottingham city centre. Despite the station locations and local transport systems remaining unchanged for both the base case and the proposed scenario, and with a similar station-to-station time of 57 minutes for Nottingham and 58 minutes for Derby in the HSR scenario, the difference likely arises from the superior accessibility provided by the conventional service in the base scenario from Derby to London compared to Nottingham. Specifically, the average station-to-station time from Derby city centre to London is 93 minutes in the base case, whereas it is 106 minutes from Nottingham city centre.

Figure 5.15 shows the spatial distribution of total journey time from East Midlands to London. The x-axis represents different journey time ranges, and the y-axis represents the frequency. In the base case, the total journey time range is from 163 to 273 minutes. However, for the scenarios, this range narrows down to durations falling within 120 to 225 minutes. Notably, the journey time range of 223-233 minutes exhibits a high frequency, occurring 131 times. In Scenario 1, a prominent peak is observed in the journey time range of 169-177 minutes with a frequency of 149. In Scenario 2, the highest frequency is 122, followed by 119, 105, and 103 within the wider range of 145 to 177 minutes. Additionally, Scenario 2 demonstrates lower frequencies for journey time ranges below 137 minutes and above 193 minutes, indicating that fewer journeys fall within these duration ranges. This insight from the histogram aids in comprehending the typical journey durations and the distribution of travel times for this specific route.

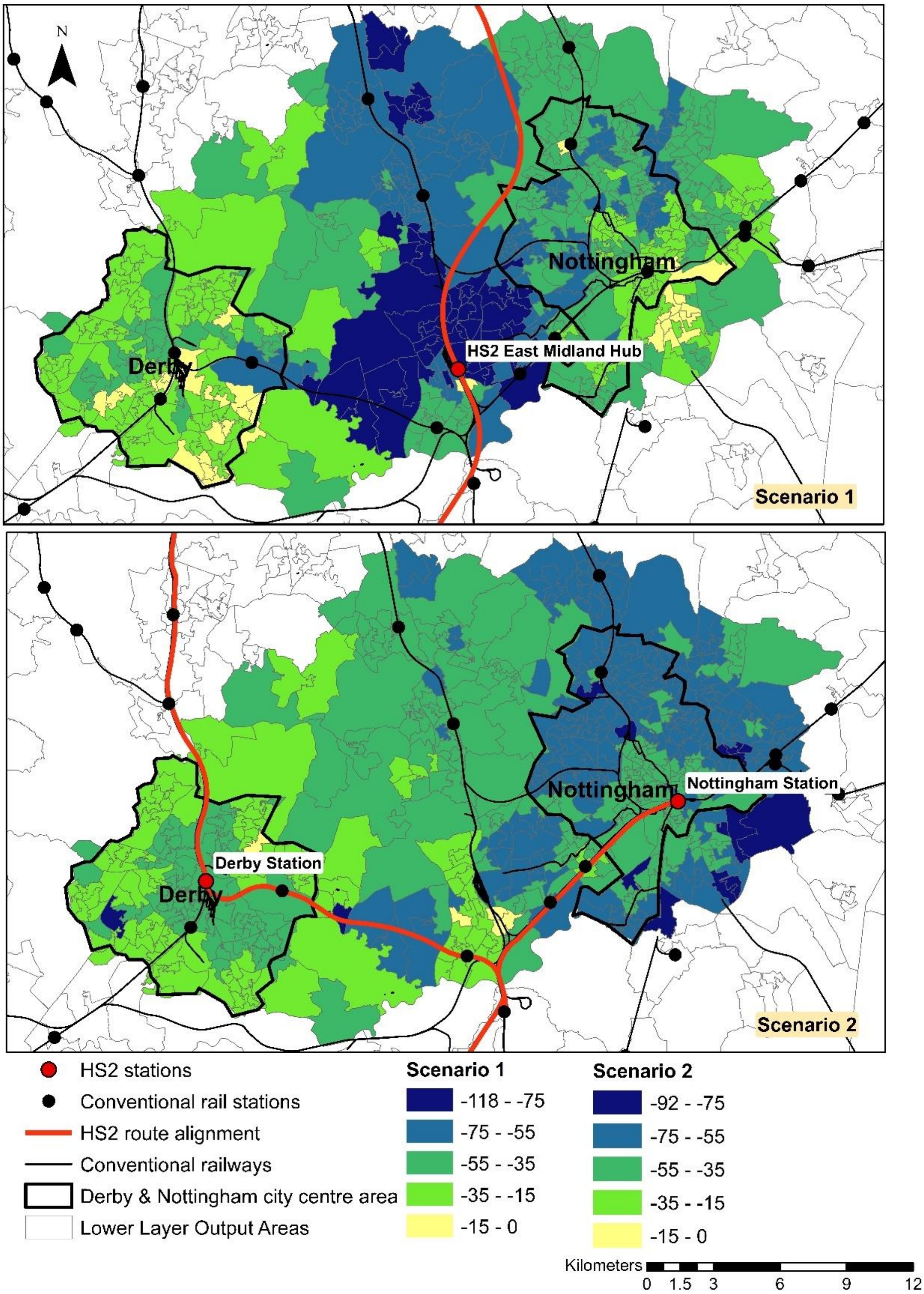


Figure 5.15 Journey time (minutes) change to London per zones

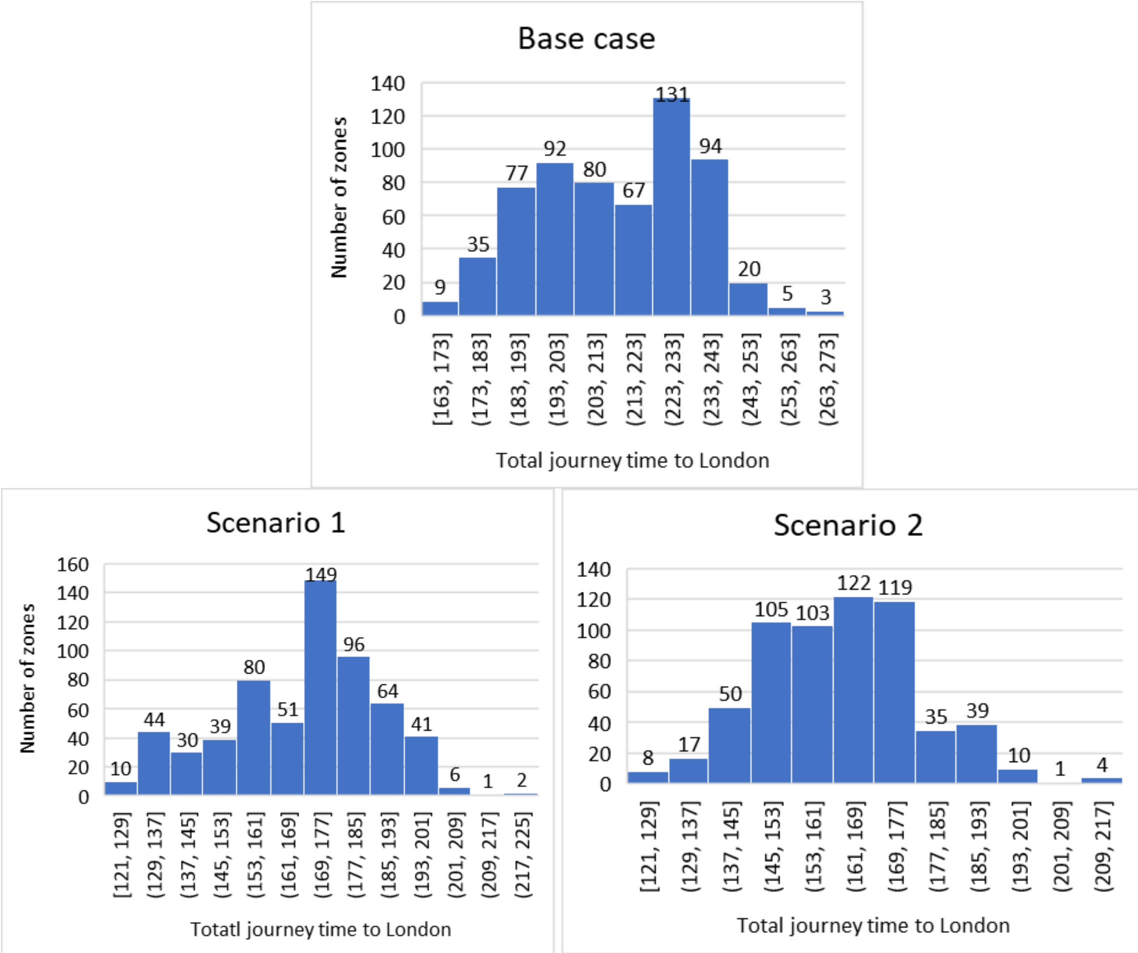


Figure 5.16 Spatial distribution of total journey time

Figure 5.16 illustrates the total journey time across different time periods—7:00 am, 11:00 am, and 5:00 pm—for both the base case and two scenarios. This temporal variation provides valuable insights into the variations in service frequencies and congestion levels throughout the day. Public transportation systems often adjust their service frequencies based on the time of day. For instance, during peak hours such as 7:00 am and 5:00 pm, when commuters are traveling to and from work, transportation services might operate at higher frequencies to accommodate the increased demand. This can result in shorter waiting times and overall faster journey times. Conversely, during off-peak hours like 11:00 am, service frequencies may be lower, leading to longer waiting times and potentially slower journey times.

In the base case, notable changes are observed in the core of Derby centre and the northern area of Nottingham centre. Scenario 1 reveals significant changes around the HS2 station and Nottingham city centre. In scenario 2, substantial changes are around Nottingham city centre. The zones between both city centres and in Derby centre exhibit higher accessibility levels at 11:00 am across all cases compared to other time periods. Conversely, the Nottingham centre area shows the highest accessibility at 7:00 am.

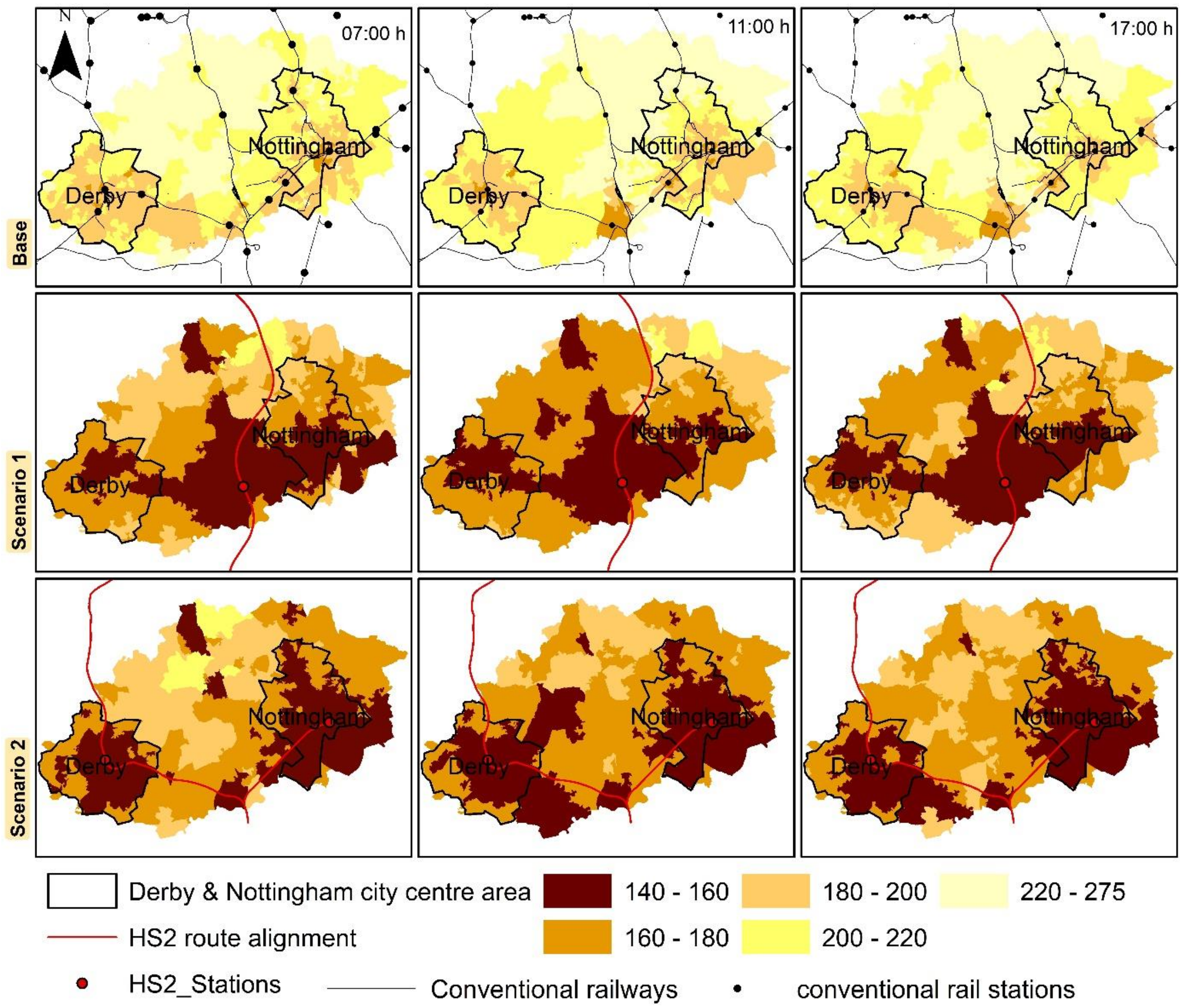


Figure 5.17 Temporal variation of spatial distribution of total journey time to London

The number of people affected by accessibility changes can be a good criterion to compare the proposed scenarios (Guthrie et al., 2017). Table 5.2 presents the cumulative percentage of population and employment within different total travel time thresholds to London for three different scenarios: Base, Scenario 1, and Scenario 2. The time thresholds are given in minutes (120, 150, 180, 210, 240, and 360).

The construction of both scenarios provides almost all people within the study area to reach destinations across Great London in less than 210 minutes. At the 150 minutes of total travel time to London, Base scenario accounts for 0.5% of the population and employment within this threshold. However, this significantly increases to 18.3% and 17.8% for Scenario 1, and further to 22.2% and 19.4% for Scenario 2, respectively. The trend continues for the 180-, 210-, and 240-minutes thresholds, where both Scenario 1 and Scenario 2 show substantial improvement compared to the Base scenario. Especially, the percentage of population and employment with access to London within 180 minutes experiences a significantly increase. In general, Scenario 2 tends to offer slightly higher percentages of population and employment falling under the specified travel time thresholds.

Table 5.2 Cumulative percentage of population and employment within different total travel time thresholds to London

| | PERCENTAGE OF POPULATION (%) | | | PERCENTAGE OF EMPLOYMENT (%) | | |
|---|---|---|---|---|---|---|
| **TIME (MIN)** | **Base** | **Scenario 1** | **Scenario 2** | **Base** | **Scenario 1** | **Scenario 2** |
| **120** | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 |
| **150** | 0.5 | 18.3 | 22.2 | 0.6 | 17.8 | 19.4 |
| **180** | 5.2 | 78.2 | 88.4 | 5.4 | 76.6 | 87.4 |
| **210** | 47.8 | 99.6 | 99.4 | 45.1 | 99.6 | 99.4 |
| **240** | 91.3 | 100.0 | 100.0 | 90.8 | 100.0 | 100.0 |
| **360** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

The disaggregated journey time can reveal the contribution of each journey stage to accessibility. The time components include access time, waiting time, transfer time, in-vehicle time, egress time, and D2D time. Table 5.3 summarises a statistical evaluation of different journey stages in the base case (current situation) and two scenarios (Scenario 1 and Scenario 2) for travel to London. The table provides the mean (average) and standard deviations (sd) for each journey stage in minutes, as well as the percentage contribution of each stage to the total D2D time.

Access time is the time spent on initial public transit or walking to the rail station. In Scenario 2, there is almost no differences in the average access time compared to the Base case. In Scenario 1, however, the average access time increases from 32.6 to 43.5 minutes, which could mean a decrease in accessibility. Also, the sd increases to 18.5 minutes, meaning a larger variability in access times among passengers. Waiting time does not show substantive differences for both scenarios. Base case, Scenario 1 and Scenario 2 are 8.6 minutes, 8.4 and 9.3 minutes, respectively.

Transfer time refers to the duration between transferring from one train to another during a journey that involves multiple train connections. The transfer times are similar to both scenarios. However, in Scenario 2, the sd of transfer time is slightly higher compared to that of scenario 1.

In-vehicle time refers to total duration spent inside the train while travelling from the origin station to the destination station. There is a substantive decrease in the average in-vehicle time in both Scenarios 1 and 2 compared to the Base case (from 109.8 minutes to 62.6 and 65.9 minutes, respectively). However, Scenarios 1 and 2 show similar decreases in average in-vehicle time.

The egress time, which refers to the duration required for passengers to exit the train station and then reach their destination, appears to exhibit a similar condition for both scenarios. This consistency could be attributed to the fact that the destination station for both scenarios is London Euston. In the base case, egress time is slightly higher due to its destination station usually being St Pancras.

Notably, Scenario 2 demonstrates lower access time compared to Scenario 1, potentially leading to more efficient travel patterns. This suggests that Scenario 2 could contribute to improved overall travel experiences.

Table 5.3 Statistical evaluation of journey stages to London

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Access time** | **Waiting time** | **Transfer time** | **In-vehicle time** | **Egress time** | **D2D time** |
| **Base case** | mean | 32.6 | 11.0 | 11.1 | 109.8 | 44.2 | 213.0 |
| | sd | 13.8 | 8.6 | 7.8 | 13.2 | 3.8 | 25.5 |
| | percentage | *15%* | *5%* | *5%* | *52%* | *21%* | *100%* |
| **Scenario 1** | mean | 43.5 | 8.4 | 5.8 | 62.6 | 40.2 | 167.8 |
| | sd | 18.5 | 4.3 | 4.9 | 8.2 | 3.1 | 22.0 |
| | percentage | *26%* | *5%* | *3%* | *37%* | *24%* | *100%* |
| **Scenario 2** | mean | 32.7 | 9.3 | 6.6 | 65.9 | 40.5 | 161.6 |
| | sd | 13.9 | 6.2 | 6.3 | 7.0 | 3.1 | 19.1 |
| | percentage | *20%* | *6%* | *4%* | *41%* | *25%* | *100%* |
| *sd: standard deviation* | | | | | | | |

Additionally, one-way ANOVA analysis is conducted to determine if the means of these three scenarios are significantly different from each other. ANOVA gives result if there are differences among group means, but not what the differences are. To find out which groups are statistically different from one another, a Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc test for pairwise comparisons was performed. The Table 5.4 shows the results of the one-way ANOVA along with the Tukey post-hoc multiple comparisons. A one-way ANOVA revealed that there is a statistically significant difference in the mean of three scenarios between at least two groups ($F(2, 1844) = [919.2]$, $p = 0.000$). Tukey post hoc test for multiple comparisons found that there are statistically significant differences ($p < 0.05$) between Base scenario and Scenario 1, Base scenario and Scenario 2, Scenario1 and Scenario 2.

Table 5.4 One-way ANOVA results and Tukey Post-hoc test comparison

| | **Sum of Squares** | **Df** | **Mean Square** | **F** | **Sig.** | **Differences** |
|---|---|---|---|---|---|---|
| **Between Groups** | 963932.7 | 2 | 481966.3 | 991.2 | 0.000 | Base – Scenario 1<br>Base – Scenario 2<br>Scenario 1 – Scenario 2 |
| **Within Groups** | 896618 | 1844 | 486.4 | | | |
| **Total** | 1870550.7 | 1846 | | | | |

Passengers do not perceive all stages of a journey in the same manner, as pointed out by Martin, (1997). Therefore, the application of weighted factors becomes essential to capture the perspectives of travellers for each stage of their journey. In this context, as discussed in Chapter 3, Section 3.4, based on the study of Román et al., (2014), the assigned weighted factors are as follows: an importance factor of 1.25 is attributed to both access and egress times. This indicates that these stages carry relatively higher significance from the traveller's point of view compared to in-vehicle time. Furthermore, a weighted factor of 2.6 is assigned to both waiting time and transfer time, signifying that these stages have an even greater impact on the overall perception of the journey. Table 5.5 provides the results with weighted factors that consider the traveller's perspective for each journey stage.

The percentage signifies the relative contribution of each stage to the total D2D time. When considering the weighted factors, the analysis reveals a significant alteration in the relative contribution of each journey stage. This emphasises the increased influence of out-of-vehicle time (including access, egress, waiting, and transfer time), accompanied by a reduction in the contribution of in-vehicle time.

In scenario 1, the non-weighted analysis showed that access time, waiting time, transfer time, and egress time contributed 26%, 5%, 3%, and 24% respectively. However, when considering the weighted factors, these contributions increased to 27%, 11%, 7%, and 25% respectively. On the other hand, the contribution of in-vehicle time decreased from 37% to 31% when weighted.

In Scenario 2, the non-weighted analysis showed that access time, waiting time, transfer time, and egress time contributed 20%, 6%, 4% and 25% respectively. However, when considering the weighted factors, these contributions increased to 21%, 12%, 9%, and 25% respectively. On the other hand, the contribution of in-vehicle time decreased from 41% to 33% when weighted.

Table 5.5 Statistical evaluation of generalised journey stages to London

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **W. access time** | **W. waiting time** | **W. transfer time** | **W. in-vehicle time** | **W. egress time** | **W. D2D time** |
| **Base case** | mean | 40.7 | 28.5 | 28.7 | 109.7 | 55.2 | 263.0 |
| | sd | 17.2 | 22.3 | 20.4 | 13.2 | 4.8 | 39.0 |
| | percentage | *16%* | *11%* | *11%* | *42%* | *21%* | *100%* |
| **Scenario 1** | mean | 54.3 | 21.9 | 15 | 62.6 | 50.2 | 204.1 |
| | sd | 23.1 | 11.2 | 12.5 | 8.2 | 3.9 | 29.2 |
| | percentage | *27%* | *11%* | *7%* | *31%* | *25%* | *100%* |
| **Scenario 2** | mean | 40.9 | 24.1 | 17.2 | 65.8 | 50.6 | 198.7 |
| | sd | 17.3 | 16.2 | 16.3 | 7 | 3.8 | 28.8 |
| | percentage | *21%* | *12%* | *9%* | *33%* | *25%* | *100%* |
| *sd: standard deviation* | | | | | | | |

The meta-study conducted by Wardman et al. (2016) revealed that for inter-urban journeys, access time has a multiplier of 1.9, while wait time has a multiplier of 1.5. This indicates that waiting time has less impact than access time, in contrast to the findings of Román et al. (2014). Further details on this comparison can be found in Section 3.4. Figure 5.17 shows a comparison of average generalised journey time components across all zones in the study area based on findings of both studies. Three distinct shapes represent different scenarios, while colours show the values for different journey time components. Access and egress time increased in the range of 20-30 minutes, while waiting and transfer time decreased in the range of 5-15 minutes. The change in D2D journey time reflects the overall impact of varying weight values, which have increased across all scenarios. The Wardman GJT times lead to an increase in average D2D journey time. However, since this increase is consistent across all scenarios, so is unlikely to have a substantial impact on which scenario is the 'best' option.

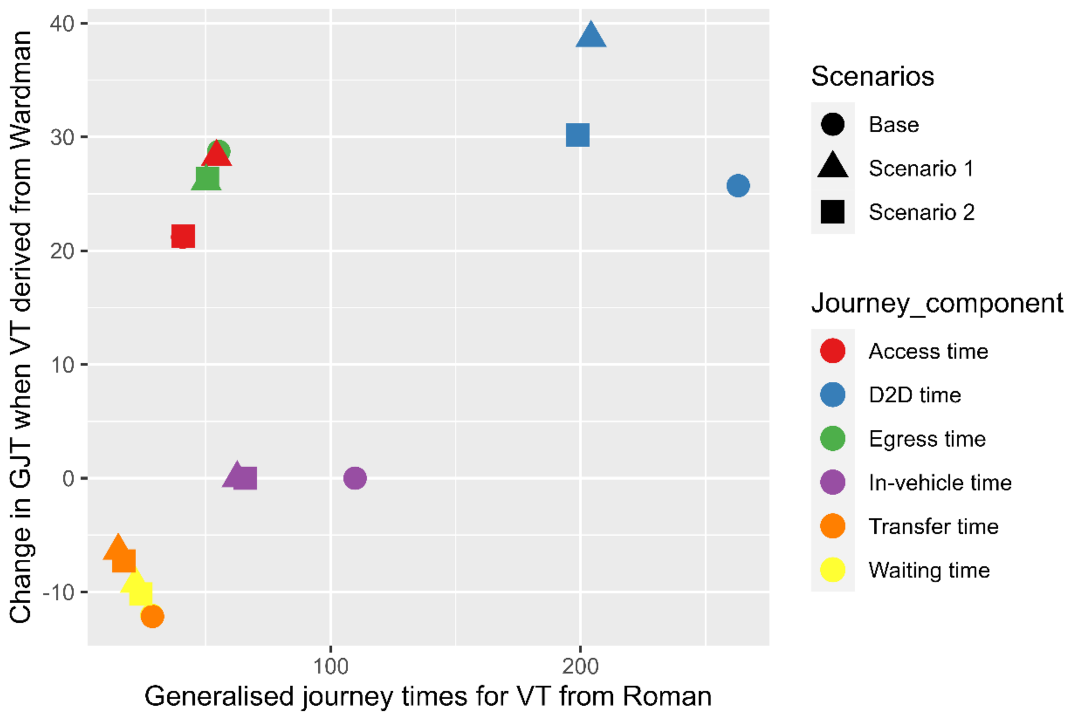


Figure 5.18 Comparison of generalised journey time components for different values of time

#### 5.7.3.1.2 To West Midlands

In the base scenario, the station-to-station journey times from Derby and Nottingham to West Midlands (New Street station) are approximately 43 and 70 minutes, respectively. However, Scenario 2 is expected to significantly reduce travel time from Derby and Nottingham to West Midlands (Curzon Street station) to just 25 minutes. In Scenario 1, the station-to-station travel time between East Midlands Hub and Curzon Street station is 20 minutes, but reaching the city centre of Nottingham and Derby necessitates a train change at East Midlands Hub. Figure 5.18 explicitly visualizes the spatial distribution of the changes in total journey time to West Midlands between the base case and proposed scenarios. Regarding the journey between Derby and Nottingham and West Midlands, it is expected that there will be less significant changes in journey time due to the relatively short distance between these regions.

In Scenario 1, there is an observed reduction of 90 minutes in the total journey time in the most extreme instances. Similar to the journey to London, the regions situated to the north of the new

East Midlands hub experience significant benefits. However, this benefit is not as spread as seen in the journey to London. In scenario 2, the average travel time to the West Midlands has decreased by 77 minutes in extreme case. Nottingham city centre and surrounding area have much more accessibility improvement compared to Derby city centre.

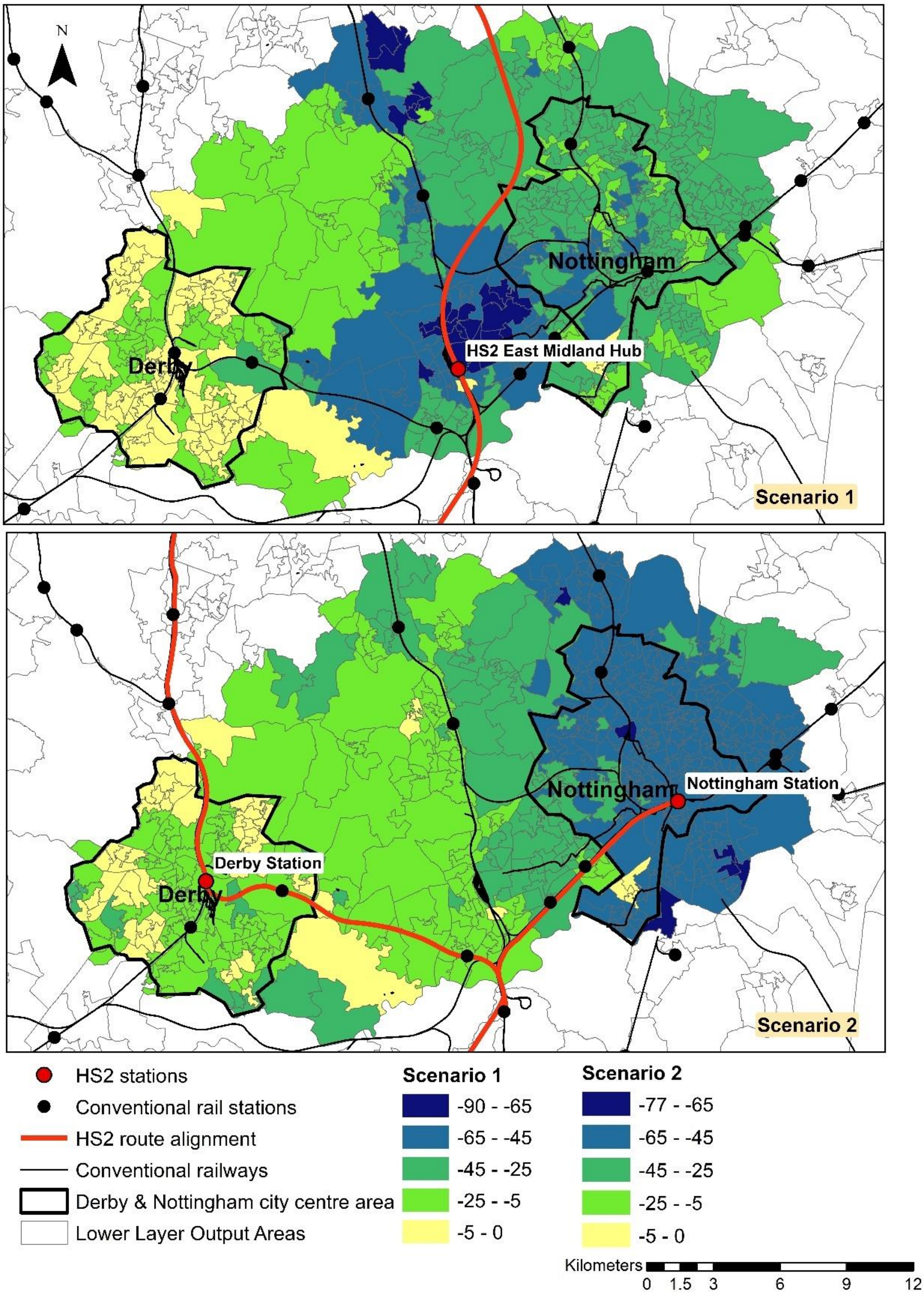


Figure 5.19 Journey time (minutes) change to Birmingham per zones

Figure 5.19 shows the spatial distribution of total journey time from East Midlands to West Midlands. In the base case, the total journey time range spans from 104 to 244 minutes. However, this range for scenarios falls within the 74 to 224 minutes duration. Notably, the journey time range of 164-174 minutes exhibits a high frequency, occurring 135 times. In Scenario 1, the highest frequency occurs within the 143-151 minutes interval, with a frequency of 100. The lower frequencies for journey time ranges below 103 minutes and above 167 minutes, indicating that fewer journeys fall within these duration ranges. Scenario 2 exhibits a highest frequency for the 127-135 minutes, the lower frequencies are below 103 and above 143 minutes.

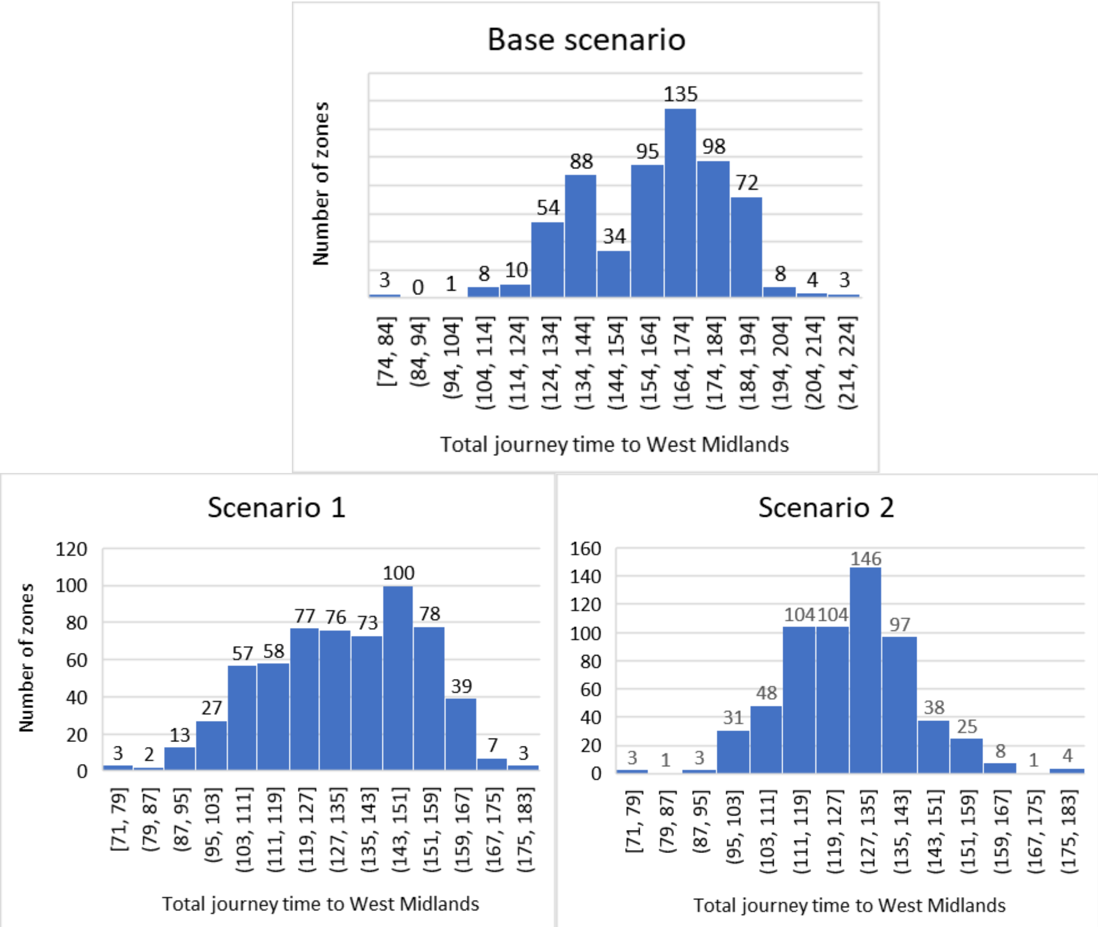


Figure 5.20 Spatial distribution of total journey time

Figure 5.20 illustrates the total journey time across different time periods—7:00 am, 11:00 am, and 5:00 pm—for both the base case and two scenarios. Across all scenarios, significant changes are observed in the Derby centre zones and the northern area of Nottingham centre. Accessibility levels in Derby centre and between both city centres are notably higher at 11:00 and 17:00. Conversely, the northern area of Nottingham centre exhibits higher accessibility levels at 7:00 am, with potentially higher service frequency during morning hours in this region.

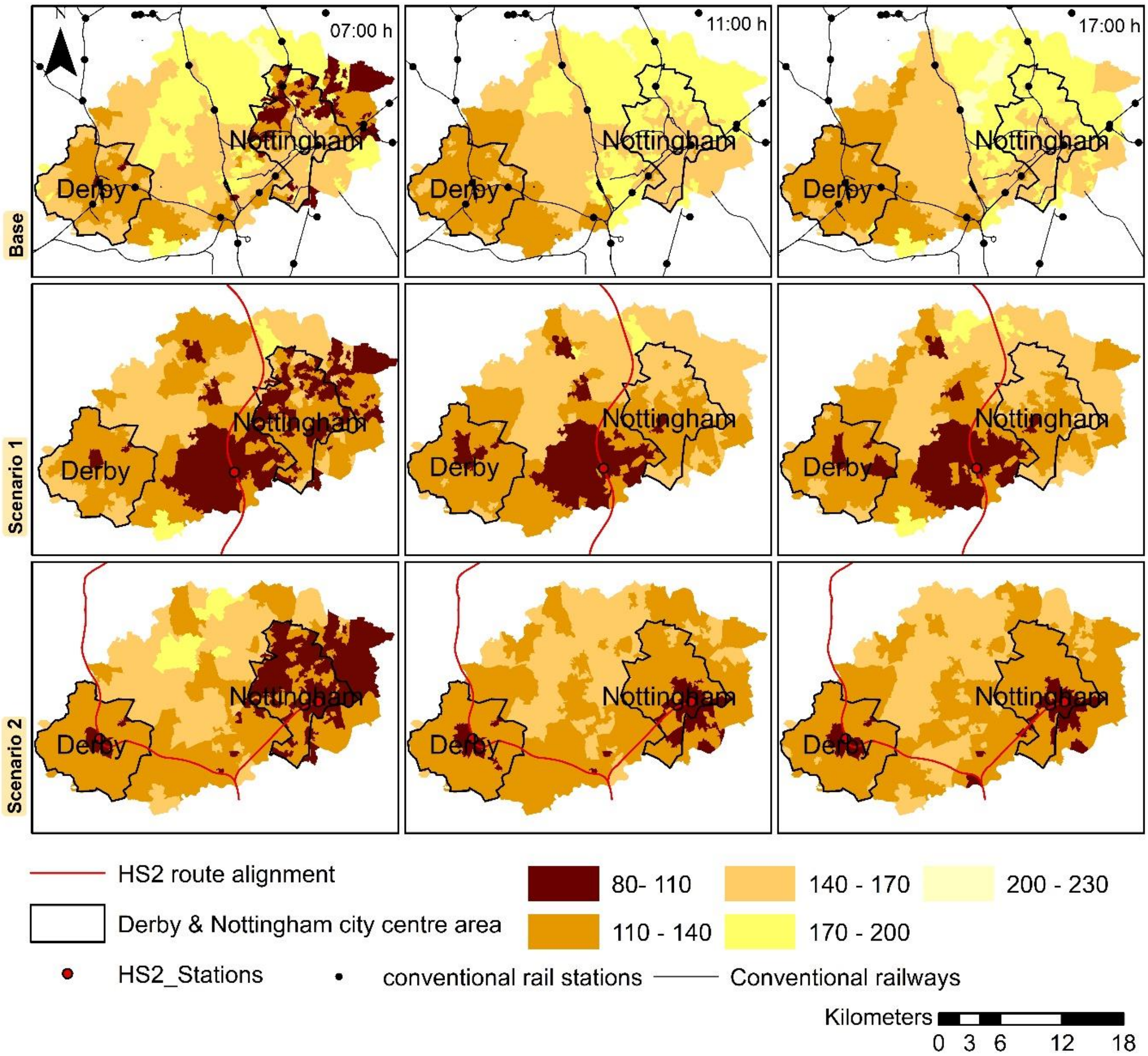


Figure 5.21 Temporal variation of spatial distribution of total journey time to West Midlands

Table 5.6 shows the percentage of population and employment within different total travel time thresholds to Birmingham for three scenarios: Base case, Scenario 1, and Scenario 2. The time thresholds are ranging from 120 to 240 minutes. The construction of both scenarios provides almost all people within the study area to reach destinations across West Midlands in less than 180 minutes. In Scenario 1, the percentage increases to 29.2% for population and 27.6% for employment, and further increases for higher time thresholds. For example, 78.0% of the population and 76.8% of employment are within 180 minutes of travel time to West Midlands. In Scenario 2, the percentage is even higher, with 35.6% of the population and 32.5% of employment within 120 minutes of travel time to West Midlands. The percentage increases significantly for higher time thresholds, with 93.5% of the population and 93.1% of employment within 150 minutes of travel time.

Table 5.6 Cumulative percentage of population and employment within different total travel time thresholds to West Midlands

| | PERCENTAGE OF POPULATION (%) | | | PERCENTAGE OF EMPLOYMENT (%) | | |
|---|---|---|---|---|---|---|
| **TIME (MIN)** | **Base** | **Scenario 1** | **Scenario 2** | **Base** | **Scenario 1** | **Scenario 2** |
| **120** | 4.3 | 29.2 | 35.6 | 4.0 | 27.6 | 32.5 |
| **150** | 31.2 | 78.0 | 93.5 | 31.4 | 76.8 | 93.1 |
| **180** | 81.0 | 99.8 | 100.0 | 80.2 | 99.7 | 100.0 |
| **210** | 99.5 | 100.0 | 100.0 | 99.5 | 100.0 | 100.0 |
| **240** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 5.7 presents a statistical assessment of journey stages to the West Midlands for three scenarios: the Base case, Scenario 1, and Scenario 2. The mean D2D times are as follows: Base case (160.4 minutes), Scenario 1 (132.2 minutes), and Scenario 2 (126.6 minutes). For access time, the values for the Base case, Scenario 1, and Scenario 2 are 35.8, 39.1, and 32.5, respectively. Notably, there are no significant differences between the scenarios and the base case in terms of access time. Regarding the standard deviation for access time, Scenario 1 exhibits the highest value at 17.1, followed by the Base case with 16.1, and Scenario 2 with the lowest value of 13.3 minutes. A lower standard deviation implies better spatial equality across regions, indicating that Scenario 2 can potentially offer improved equality in this context.

Table 5.7 Statistical evaluation of journey stages to West Midlands

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Access time** | **Waiting time** | **Transfer time** | **In-vehicle time** | **Egress time** | **D2D time** |
| **Base case** | mean | 35.8 | 9.8 | 11.6 | 69.4 | 32.7 | 160.4 |
| | sd | 16.1 | 6.8 | 7.1 | 17.3 | 7.1 | 24.4 |
| | percentage | *22%* | *6%* | *7%* | *43%* | *20%* | *100%* |
| **Scenario 1** | mean | 39.1 | 10.3 | 7.9 | 36.2 | 36.9 | 132.2 |
| | sd | 17.1 | 5.2 | 6.2 | 10.8 | 6.3 | 22.0 |
| | percentage | *30%* | *8%* | *6%* | *27%* | *28%* | *100%* |
| **Scenario 2** | mean | 32.5 | 8.9 | 7.7 | 38.8 | 36.8 | 126.6 |
| | sd | 13.3 | 5.6 | 6.0 | 8.0 | 6.2 | 17.8 |
| | percentage | *26%* | *7%* | *6%* | *31%* | *29%* | *100%* |
| *sd: standard deviation* | | | | | | | |

In addition, a one-way ANOVA analysis is conducted to assess whether there are significant differences among the means of three scenarios. The ANOVA test indicated that there is indeed a statistically significant difference in the mean values of the scenarios ($F(2, 1844) = [433.3]$, $p = 0.000$). However, ANOVA alone does not specify which specific groups exhibit significant differences. To determine the pairwise differences between groups, a Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc test is performed. Table 5.8 shows the results of the one-way ANOVA along with the Tukey post-hoc multiple comparisons. The results of the Tukey post-hoc test revealed statistically significant differences ($p < 0.05$) between the Base scenario and

Scenario 1, between the Base scenario and Scenario 2, as well as between Scenario 1 and Scenario 2.

Table 5.8 One-way ANOVA results and Tukey Post-hoc test comparison

| | Sum of Squares | Df | Mean Square | F | Sig. | Differences |
|---|---|---|---|---|---|---|
| **Between Groups** | 403407 | 2 | 201704 | 433.3 | 0.000 | Base – Scenario 1<br>Base – Scenario 2<br>Scenario 1 – Scenario 2 |
| **Within Groups** | 858868 | 1844 | 466 | | | |
| **Total** | 1262275 | 1846 | | | | |

Table 5.9 provides the results with weighted factors that consider the traveller's perspective for each journey stage to Birmingham. The percentage indicates the relative contribution of each stage to the total D2D time. When considering weighted factors, the analysis demonstrates a noticeable change in the relative contribution of each journey stage, highlighting the increased impact of out-of-vehicle time (access, egress, waiting, and transfer time) and a decrease in the contribution of in-vehicle time.

In Scenario 1, the non-weighted analysis showed that waiting time and transfer time contributed 8% and 6% respectively. However, when considering the weighted factors, these contributions increased to 15% and 11% respectively. On the other hand, the contribution of access time, in-vehicle time and egress time decreased from 30%, 27%, 28% to 27%, 20%, 26% when weighted.

In Scenario 2, the non-weighted analysis showed that waiting time and transfer time contributed 7% and 6% respectively. However, when considering the weighted factors, these contributions increased to 14% and 12% respectively. On the other hand, the contribution of access time, in-vehicle time and egress time decreased from 26%, 31%, 29% to 24%, 23%, 27% when weighted.

Table 5.9 Statistical evaluation of generalised journey stages to West Midlands

| | STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **W. access time** | **W. waiting time** | **W. transfer time** | **W. in-vehicle time** | **W. egress time** | **W. D2D time** |
| **Base** | mean | 44.7 | 25.4 | 30.1 | 69.4 | 40.9 | 210.5 |
| | sd | 20.1 | 17.7 | 18.6 | 17.3 | 8.9 | 35.2 |
| | percentage | *21%* | *12%* | *14%* | *33%* | *19%* | *100%* |
| **Scenario 1** | mean | 48.9 | 26.7 | 20.4 | 36.2 | 46.1 | 178.3 |
| | sd | 21.4 | 13.6 | 16.2 | 10.8 | 7.9 | 33.4 |
| | percentage | *27%* | *15%* | *11%* | *20%* | *26%* | *100%* |
| **Scenario 2** | mean | 40.6 | 23.2 | 20.0 | 38.8 | 46.0 | 168.6 |
| | sd | 16.7 | 14.5 | 15.5 | 8.0 | 7.7 | 27.4 |
| | percentage | *24%* | *14%* | *12%* | *23%* | *27%* | *100%* |
| ***sd: standard deviation*** | | | | | | | |

Wardman et al. (2016) conducted a meta-analysis revealing that for inter-urban travels, access time is weighted with a multiplier of 1.9, whereas wait time is attributed a multiplier of 1.5. This indicates that access time has greater impact compared to wait time, which contrasts with the findings of Román et al. (2014). Further detail on this comparison is available in Section 3.4. Figure 5.21 shows a comparison of average generalised journey time components across all zones in the study area based on findings of both studies. The figure shows three distinct shapes representing different scenarios, with colours showing the values for different journey time components. Access and egress time shows a rise within the 20-30 minutes range, whereas waiting and transfer time exhibits a decrease ranging from 5-15 minutes. The change in D2D journey time reflects the collective influence of varying weight values, which have risen across all scenarios. Wardman's generalised journey time values resulted in a boost in average D2D journey time. Nevertheless, given that this increase is uniform across all scenarios, it is improbable to significantly influence the determination of the optimal scenario.

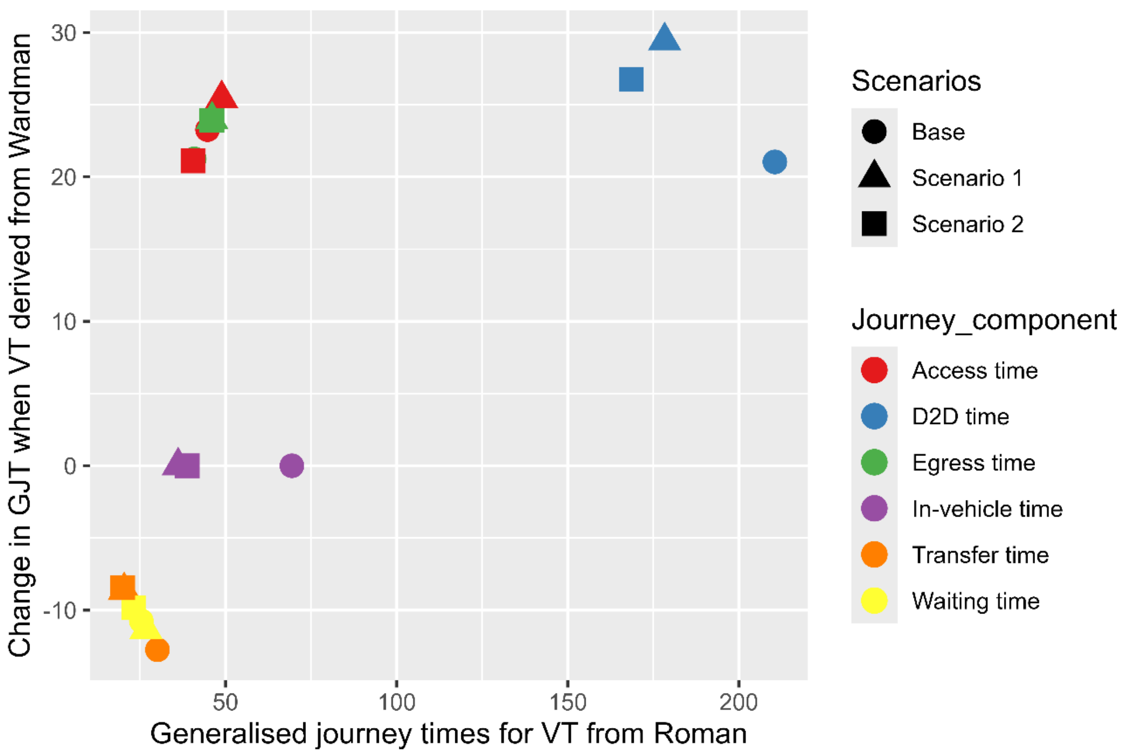


Figure 5.22 Comparison of generalised journey time components for different values of time

#### 5.7.3.2 Weighted Average Travel Time change

In the previous section, the analysis primarily centred on the comprehensive door-to-door journey time to assess accessibility differences throughout the city. It then evaluated the impact of understanding the generalised journey time on each journey stage. However, the spatial variation itself was not explicitly presented. In this section, a comparison is made between two indicators, highlighting their differences in terms of spatial variation. This comparison illustrates how different factors or measures contribute to variations in accessibility across different areas of the city.

Door-to-door journey time (D2D) is a simple accessibility indicator that averages the travel time from a specific location to all other possible locations. This measure assumes all destinations are equally important, regardless of their characteristics such as population, which may not always reflect real-world scenarios.

Weighted Average Travel Time (WATT) is more advanced accessibility measure, considering the attractiveness of diverse destinations during the computation of the average travel time. The equation for calculating WATT is presented in Chapter 3, Section 3.5. The notion of attractiveness could be represented by factors like gross domestic product (GDP), employment, or population of the destination. In this particular study, the population factor is adopted, implying that locations with larger populations will exert a greater influence on the overall average. For instance, if a location is far away but highly populated, it would affect the WATT more significantly than a close but less populated location. This can be more useful in real-world applications, where certain destinations (like major destinations) are more significant than others. Moreover, while calculating the WATT, a generalised journey time is employed instead of a door-to-door journey time. This signifies that the calculation takes into consideration the discomfort associated with various journey components and assigns corresponding weightage to these components.

Figure 5.22 shows the percentage change of both D2D journey time and WATT accessibility indicators for Scenario 1 and Scenario 2 across different locations in the East Midlands to London corridors. The light-yellow zones on the map represent areas where the construction of the HSR system has resulted in no enhancements in accessibility. This suggests that travellers in these zones might still favour conventional train options over HSR trains. Conversely, the darker regions on the map showcase the most substantial advantages in terms of accessibility brought about by the implementation of the new HSR system. These areas experience higher connectivity and improved access to transportation alternatives, indicating that passengers residing here are likely to derive the greatest benefits from the introduction of the HSR infrastructure.

The primary focus is not on comparing scenarios, but rather on contrasting the impacts arising from the usage of distinct indicators. Evidently, the percentage change, serving as a measure of obtained benefits, is marginally lower when assessed through WATT indicators. In Figure 5.22, the change in indicators leads to the identification of the most affected area located in the northern part of the study area for both Scenarios. It can be inferred that these zones have likely been affected by extended waiting and transfer times. Specifically for the Scenario 2, the Nottingham also displays noteworthy change due to the usage of distinct indicators.

Figure 5.23 shows the percentage change along the East Midlands to West Midlands corridors. In Scenario 1, the change is particularly concentrated around Nottingham. Conversely, in Scenario 2, these discrepancies emerge northeast of Nottingham. Interestingly, both scenarios exhibit minimal change around Derby, possibly attributed to fewer instances of transfer times across the region. It is plausible that alternative modes of public transportation to the stations are favoured in this region due to lack of train connection.

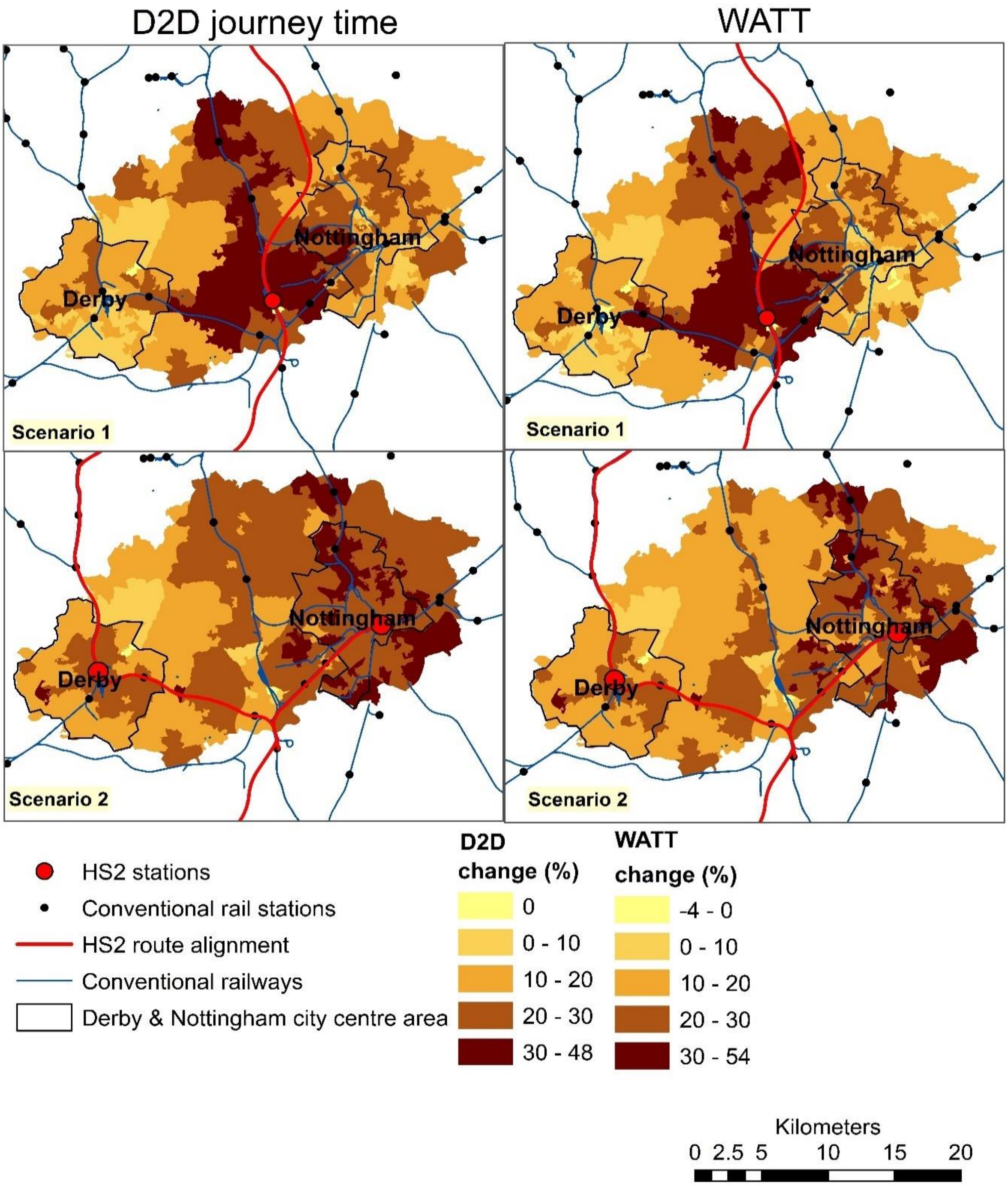


Figure 5.23 Spatial distribution of percentage change of D2D time and WATT to London

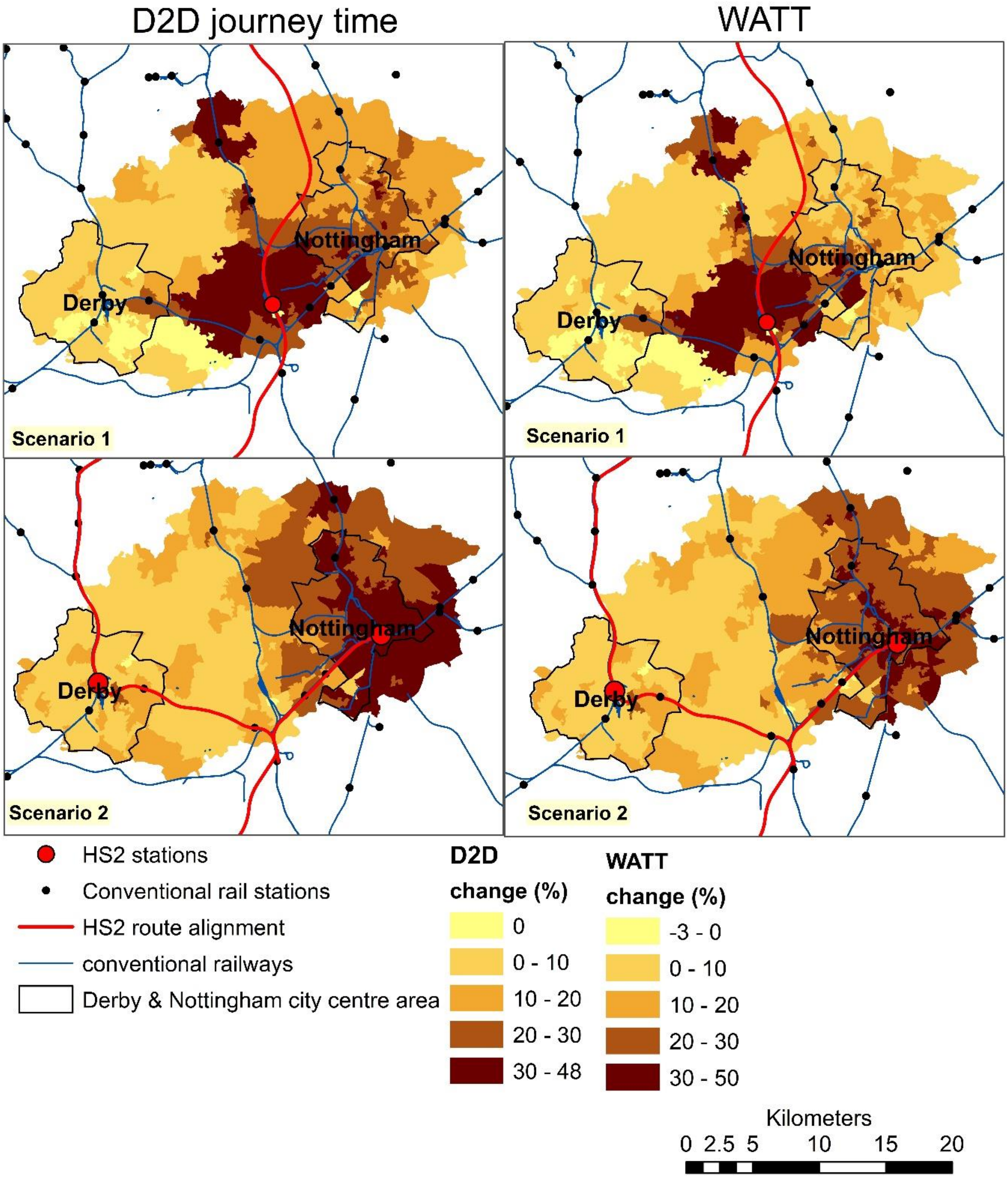


Figure 5.24 Spatial distribution of percentage change of D2D time and WATT to West Midlands

## 5.8 Conclusion

This chapter presents the practical implementation of the door-to-door approach to enhance the analysis of intercity travel accessibility. The door-to-door approach, combining both intra-city and inter-city segments, provides a comprehensive understanding of intercity travel and reveal the spatial variations of accessibility patterns across the city. The location of high-speed railway stations within cities might have a major impact on the door-to-door journey time savings delivered by high-speed rail routes.

However, there is limited evidence concerning the comparative advantages of distinct station location types in terms of door-to-door journey times at the micro-scale level. Consequently, this chapter investigated the benefits of constructing peripheral stations versus city centre stations, covering measurable distinctions between these design choices. The investigation centres on the HS2 corridors, specifically focusing on the East Midlands region, to observe the resulting changes. The significance of station location holds particular importance in the context of the UK's HS2 corridor. In previous HS2 proposals, a station was initially planned at Toton, designated as the East Midlands Hub. Subsequently, this proposal underwent revision, directing HSR services to connect directly with existing city centre stations in Derby and Nottingham. Hence, the utilisation of the corridor aligns well with the objective of the chapter.

The analysis was successfully performed through a comparison of two distinct scenarios. The results were disaggregated to a very high spatial level allowing examination of which areas of the East Midlands would benefit most from the two station location options. The findings highlight the importance of accounting for the access and egress components of rail journeys. In particular, peripheral station locations results in extended intra-city travel times, but simultaneously enhances accessibility to the outskirts of urban regions. Conversely city centre stations seamlessly integrate with local public transportation networks, minimising waiting and transfer times for passengers, all of this achieved without requiring additional investments in public transport infrastructure. In the case of the East Midlands to London corridor, the results demonstrate that the contribution of access time to the station constitutes 26 percent of the total accessibility of rail trips, on average, for peripheral stations. This value drops to 20 percent for central stations. These findings further emphasise the trade-offs involved in choosing between peripheral and city centre station locations.

It is important to note certain limitations, specifically the potential reduction in the availability of conventional railway services following to the implementation of High-Speed Rail systems. This shift could lead to adverse accessibility effects in certain areas that do not experience the advantages of HSR enhancements. The study operates under the assumption that the existing conventional rail network remains unchanged, and the current level of service remains constant. This could imply that the accessibility benefits identified in the analysis might be somewhat overestimated. To enhance the comprehensive nature of future analyses, it's recommended to monitor and incorporate forthcoming data regarding any change to railway services resulting from the introduction of HSR.

Another limitation of this study that does not consider the long-term effect that the introduction of a new peripheral HSR station has the potential to stimulate development in the surrounding area. Evaluating the land-use impacts resulting from transportation investments presents challenges, particularly when attempting to do so with a high level of spatial detail. Consequently, the current findings of the study are prone to underestimating the comprehensive extent of long-term accessibility benefits associated with the peripheral station. It is important to highlight that the study's focus is directed towards discerning the short-term impact of the HSR project on accessibility levels, and thus, the spatial distribution of the population has been maintained as a constant within the analysis.

# Chapter 6 EXAMINING THE IMPACT OF CONNECTIVITY LEVEL OF AN HSR STATION

## 6.1 Introduction

The previous chapter (Chapter 5) demonstrated that the location of a station directly influences the spatial interaction of cities by affecting access time. This chapter further contributes to the study of HSR accessibility by focusing on the analysis of a station's connectivity level in the West Midlands metropolitan county where a new high-speed railway line is due to be introduced. The question under investigation is how does the connectivity level of HSR stations affect intercity accessibility?

Each transport mode may appear as a set of separately operated networks. This design idea can result in constraints due to poor integration, interoperability and interconnection between different transport modes (Givoni and Banister, 2010). However, from a passenger's perspective, there is a single transport system that comprises various modes and the transfers between them. Therefore, in planning, the focus should be on ensuring the overall efficiency of the entire transport system and understanding how each component can enhance the others' functionality.

In particular, a rail journey is rarely an end in itself; it is almost always part of a journey “chain” that includes travel to and from the railway station using different transport modes. The seamless integration of these components is essential to achieve a continuous door-to-door journey when using rail, therefore making it competitive alternative to car travel. Overall, the access and egress stage of the journey could be an important part in the decision-making process about whether to use rail transport at all. The findings presented can assist HSR planners in better understanding the importance of the HSR station's connectivity level with existing travel modes.

## 6.2 HSR station connectivity

The connectivity level of an HSR station refers to its integration with various transportation modes, urban infrastructure, and surrounding areas. It encompasses the ease with which passengers can transfer between the HSR system and other modes of transportation, such as local trains, buses, metros, taxis, and airports. A high level of connectivity ensures smooth transitions between various transportation modes, minimising travel disruptions and enhancing the overall passenger experience. It enables passengers to seamlessly switch between HSR services and other local transportation options, reducing travel times and improving convenience.

The location of an HSR station plays a crucial role in determining its connectivity level. Stations located within or near city centres are generally more accessible and offer better integration with local transportation networks. However, it is important to note that even with a favourable location, the connectivity level of an HSR station with other transport modes can still vary. Some HSR stations may lack direct links to local train services, bus terminals, or other modes of public transportation, which can impact the overall connectivity and ease of transferring between different modes.

Tapiador, Burckhart and Martí-Henneberg, (2009) examined the interconnectivity level of European high-speed train stations itself and aimed to understand the hierarchy and constraints of these stations in terms of their ability to function optimally as intermodal nodes. Their results firstly found that intermodality is positively influenced by the presence of multiple transportation modes, such as conventional rail and regional bus services, which enhances accessibility and promotes higher intermodality. Secondly, stations with multiple vertical interconnected levels are more efficient for intermodality compared to horizontally designed stations, as they minimise transfer times and facilitate seamless mode exchange. Thirdly, coordinating timetables across different modes of transport enables passengers to plan multimodal trips effectively, further enhancing interconnectivity.

Moreover, Martí-Henneberg and Alvarez-Palau (2017) conducted a comprehensive study on the availability of complementary local transport services at 95 high-speed rail stations across various European countries. Their findings, presented in Table 6.1, show the transportation options at these stations, categorised as 60 in city centres, 9 in city edges, and 26 in peripheral areas. It was observed that many stations prioritise individual transport mobility, with approximately 92% of them offering car parking facilities and taxi services. However, the availability of underground systems, particularly in city edges and peripheral areas, is limited. This limitation can be attributed to the high investment costs associated with establishing underground systems. Similarly, the bus network is not well-developed for peripheral stations. These shortcomings in public transport services can potentially worsen the connectivity between peripherally located HSR stations and the final destinations of passengers (Diao et al., 2017). Furthermore, they may contribute to the increased preference for car travel as a complementary mode of transportation. While Table 6.1 provides insights into the connectivity between HSR stations and other modes of transport, it does not present the impact of different connectivity levels of a station on overall accessibility. This information would be more beneficial in understanding the effectiveness of these modes in connecting the HSR stations to the ultimate destinations of passengers.

Table 6.1 The percentage of available intermodal transport services at HSR stations

*Source: (Martí-Henneberg and Alvarez-Palau, 2017, p.94)*

| Station location | Parking facilities | Underground | Local bus | Taxi | Coach | Number of stations |
|---|---|---|---|---|---|---|
| Central station | 92% | 45% | 95% | 93% | 78% | 60 |
| City edge | 89% | 11% | 78% | 89% | 56% | 9 |
| Peripheral area | 92% | 4% | 27% | 88% | 69% | 26 |
| Average | 92% | 31% | 75% | 92% | 74% | 95 |

Enhancing HSR station connectivity requires the consideration of various physical and infrastructural aspects such as station design and the connection between different platforms. Additionally, operational factors, including the integration of HSR lines, efficient scheduling, fare systems, and reliable information systems, are crucial for enhancing connectivity. A study conducted by Brunello (2011) investigates the interoperability between HSR and conventional networks to enhance accessibility benefits for areas located far from HSR stations. The study evaluates three alternative strategies that consider both infrastructural and operational aspects: regional rail, interurban rail, and rapid transit. While this study explored alternative strategies to improve connectivity and accessibility beyond immediate HSR station areas, this thesis focuses on understanding the existing modes of transport available at HSR stations and their effectiveness in connecting passengers to their final destinations.

In addition to studying the interconnectivity level of HSR stations, there is also research examining the impact of connectivity on demand. The level of connectivity at an HSR station is not only crucial for ensuring a seamless journey but also plays a significant role in shaping the demand for its services. A study conducted by Teng et al. (2022) demonstrated that the characteristics of multimodal connectivity, including well-connected bus, subway, and regional railroad services, have a significant influence on attracting passengers to HSR stations and promoting ridership. This highlights the importance of considering and enhancing the intermodal connectivity of HSR stations to effectively meet passenger latent demand and foster sustainable ridership growth.

While previous studies have explored the connectivity of HSR stations, there appears to be a research gap regarding how varying levels of station connectivity impact the accessibility of the cities served by HSR lines. To the best of our knowledge, there is a lack of research specifically focusing on the relationship between station connectivity and the accessibility levels of these cities. By examining this relationship, this study aims to address this gap and provide valuable insights into the significance of interconnectivity between different modes of transportation.

## 6.3 Definition of scenarios

This study aims to empirically examine the impact of the connectivity level of the HSR station with other modes of transportation on the accessibility of the region relative to other cities. The study specifically uses the first plan of HS2, as depicted in section 5.4, and focuses on the West Midlands region to observe the resulting changes.

Scenario 1 is a hypothetical situation where Phase 1 of HS2 terminates at the existing New Street railway station. This is the largest and busiest of the three main railway stations in Birmingham city centre and acts as central hub of the British railway system (See Figure 6.1). New Street station already benefits from being well-connected to the current conventional railway network. It serves a majority of the county`s rail services, provided by West Midlands Trains, Transport for Wales, Cross Country, and Avanti West Coast. Thus, it is expected that New Street station can provide passengers with convenient access to multiple destinations, by reducing the need for additional transfers or walks to other stations.

Scenario 2 involves the inclusion of Birmingham Curzon Street railway station, which is recently under construction and planned to be the northern terminus of Phase 1 of HS2 in the city centre of Birmingham. It is expected that the station's connectivity with the current rail network is relatively limited compared to New Street station. This means that passengers using Curzon Street station may face challenges when trying to reach certain destinations that are not directly reachable by train. For instance, a passenger who wishes to travel to Wolverhampton would need to walk from Curzon Street station to New Street station to catch a train. Both scenarios have stations located in city centre, thus eliminating differences due to the location of stations in the broader urban environment. Figure 6.2 shows the relative locations of Curzon Street and New Street stations.

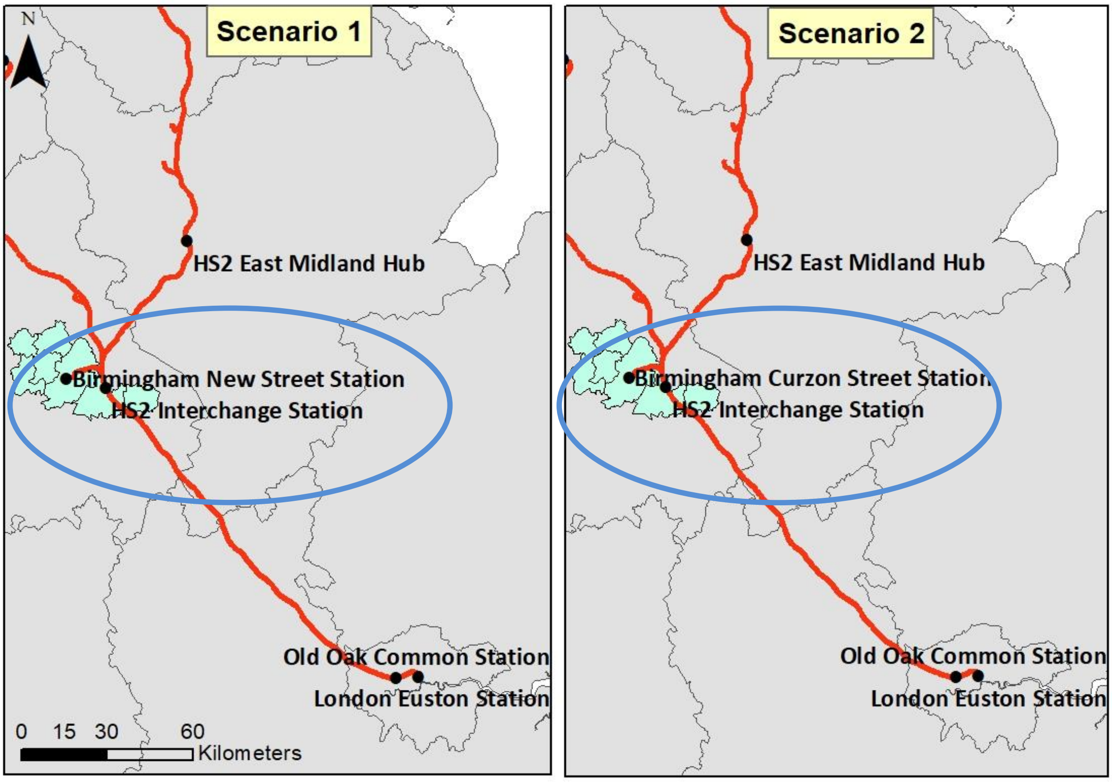


Figure 6.1 HS2 route scenarios

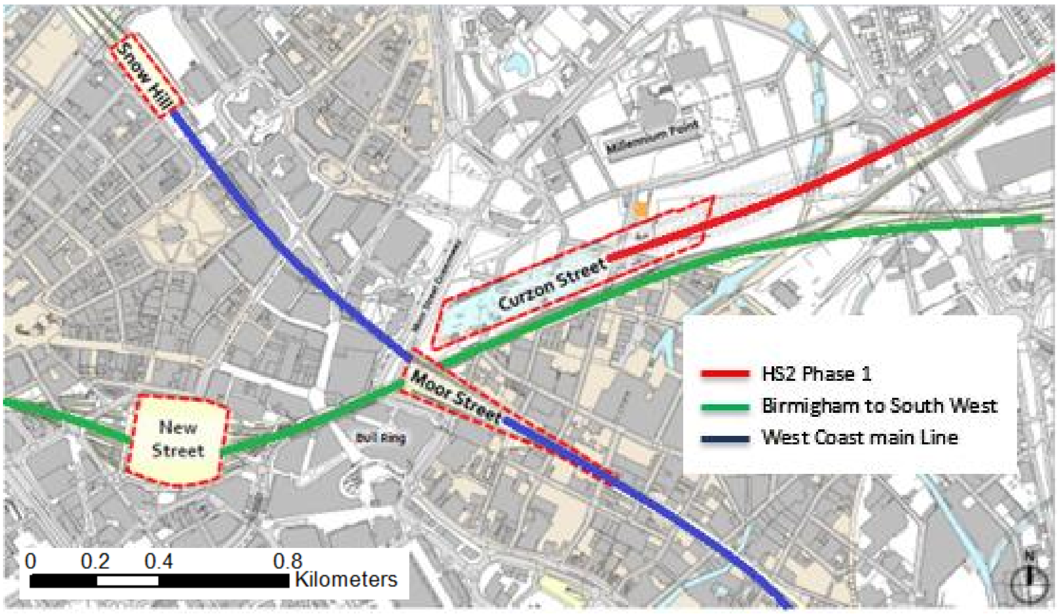


Figure 6.2 The map showing relative locations of Curzon Street and New Street stations

*Sources:* (Birmingham City Council, 2015)

Birmingham Curzon Street station will feature the creation of four new public spaces surrounding the station, see Figure 6.3, (Birmingham City Council, 2015). *Station Square* will establish a green, environmentally friendly, and appealing gathering space within the city, making it convenient to reach the city centre and Digbeth area. This development will serve as a welcoming gateway for passengers to or from Birmingham on the HS2 journey. *Curzon Square* will be designed to blend in seamlessly with the historic environment and structures in its vicinity, while also enhancing the ambiance of Eastside City Park. The square will also offer space for hosting outdoor public events.

*Curzon Promenade* is positioned along the northern side of the station and serves as a connection area to Eastside City Park. This includes garden areas that extend downwards towards Curzon Square. *Paternoster Place* will offer a pedestrian pathway and urban area that plays a crucial role in connecting to the potential future development of Digbeth. As a result, the station will have two main public entrances: one located at the west end on Moor Street Queensway, serving the City Centre Core, and another at the east end on New Canal Street, catering to Eastside and Digbeth areas.

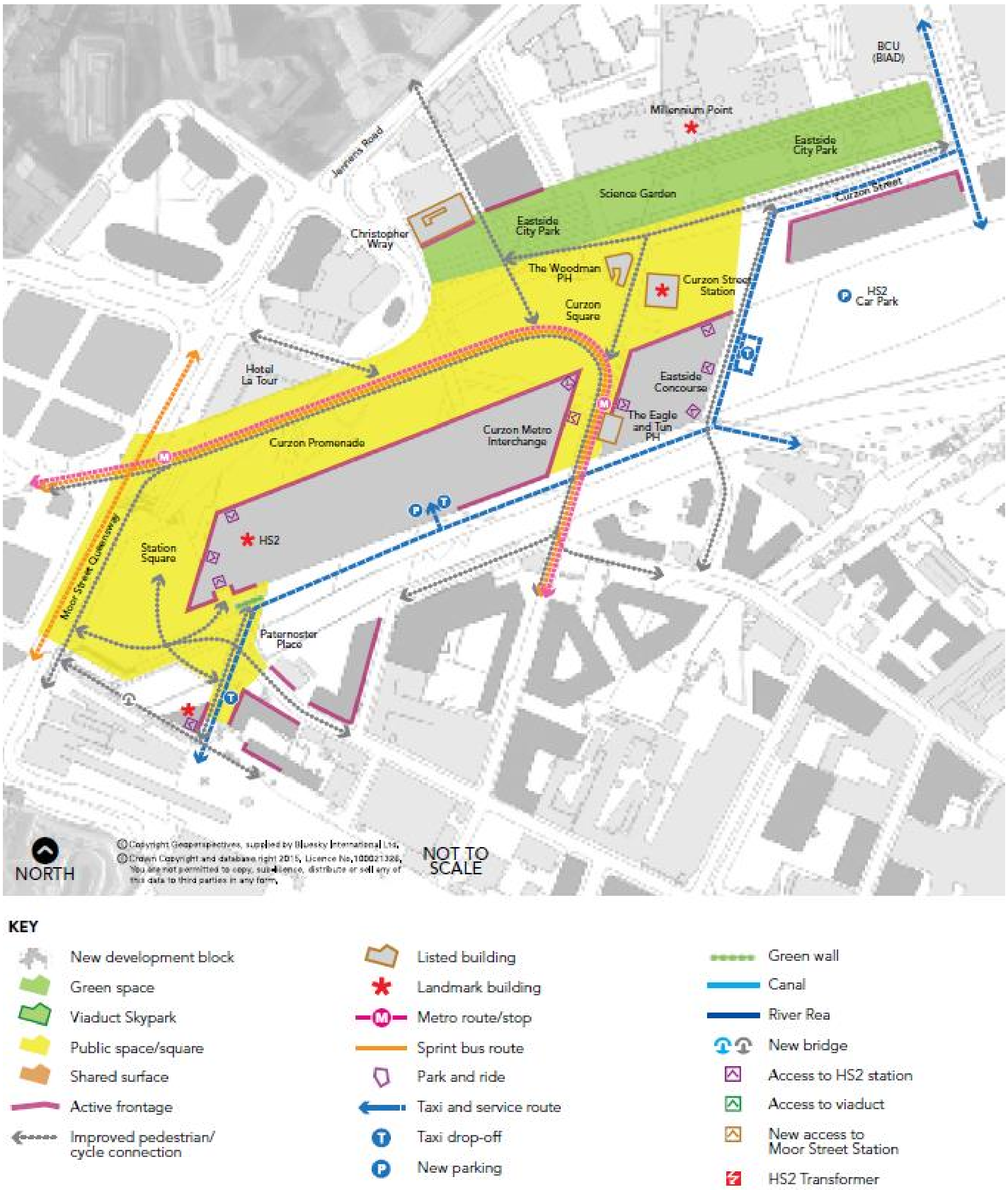


Figure 6.3 Masterplan for Curzon Street station

*Source: (Birmingham City Council, 2015)*

An important aspect of the introduction of Curzon Street station is its integration with the local transportation system. The Birmingham Eastside extension of the West Midlands Metro, a light-rail/tram system, plays a crucial role by providing Metro services to Digbeth and serving the HS2 station at Curzon Street (See Figure 6.4). The extension will start from Bull Street and terminate at a new stop at Digbeth High Street, with four new stops along the stretch. The extension will serve the Eastside regeneration, providing connections with New Street, Moor Street and Snow Hill Railway Stations, in addition to the new HS2 station.

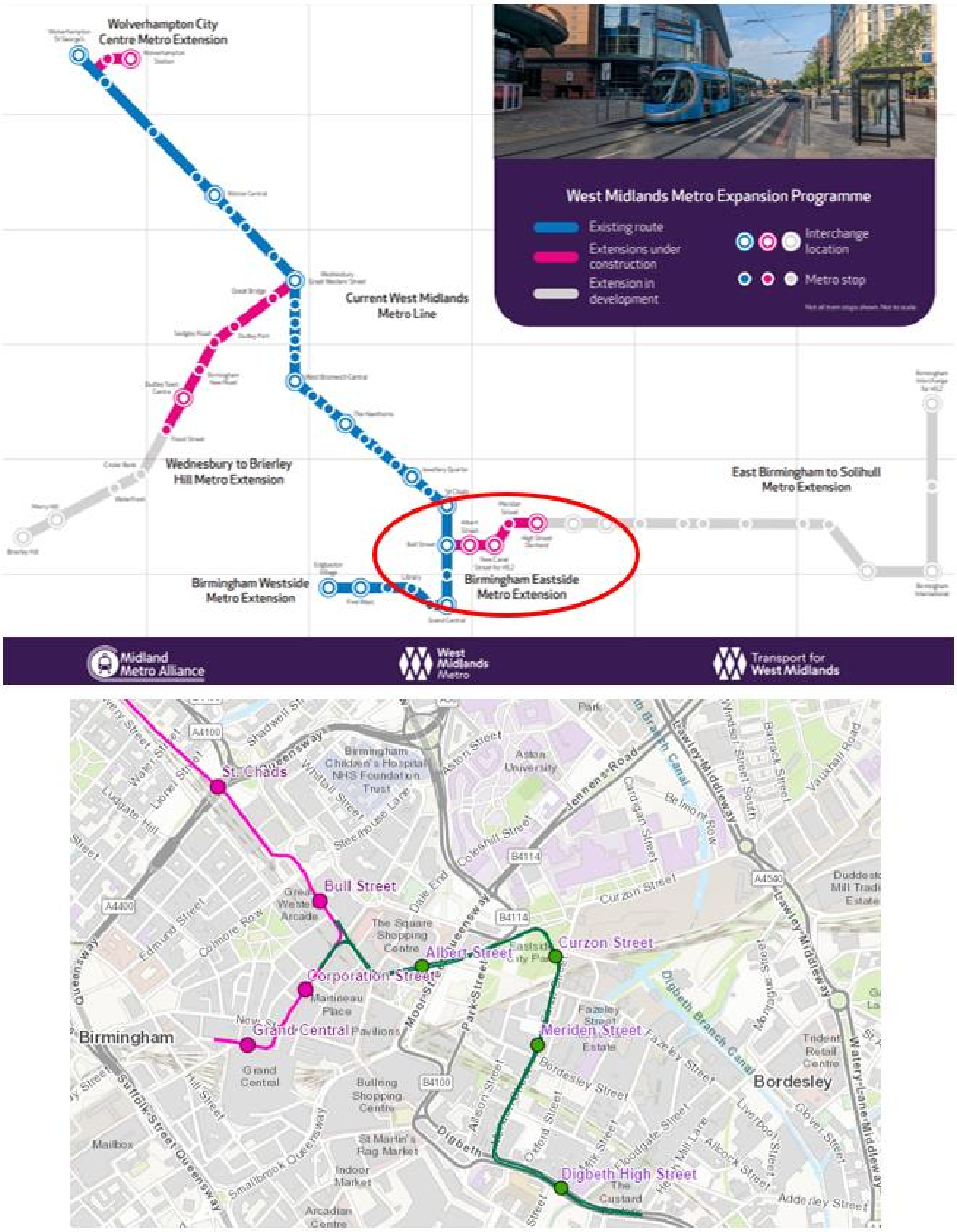


Figure 6.4 West Midland Metro Expansion for Curzon Street Station

*Source : (Midland Metro Alliance, 2022)*

## 6.4 Data Preparation

The data preparation process for the scenarios described here is the same as that outlined in Section 5.6. It involves obtaining spatial data from OpenStreetMap and timetable data in GTFS format from various sources. However, there are additional adjustments required for both Scenario 1, which includes New Street station, and Scenario 2, which involves the integration of Curzon Street station with the local public transport network.

In Scenario 1, the location of the HSR station within the timetable data needs to be adjusted to reflect New Street station. This adjustment involves updating the station information in the timetable data to accurately represent the changes made to the station's location. For Scenario 2, the integration of Curzon Street station with the local public transport network has been considered. As described in Section 6.3, the Birmingham Eastside extension of the West Midlands Metro line plays a crucial role in this integration. The extension will provide Metro services to Digbeth and serve the HS2 station at Curzon Street. It will start from Bull Street and terminate at a new stop at Digbeth High Street, with four new stops along the way. To accommodate this integration, existing timetable data for additional services has been updated. The service frequency of this metro extension is every six minutes during peak times, with a 15-minute frequency during off-peak hours. The operating hours for the Metro service are as follows: Monday to Friday: 04:40 to 00:15, Saturday: 04:40 to 01:00, Sunday: 07:20 to 00:10 (Midland Metro Alliance, 2022).

Accurately identifying origin and destination points within cities requires the determination of population-weighted geographical centroids. However, to provide an optimal trade-off between computational efficiency and precise geographic representation, it is necessary to carefully consider the choice of geographic level. In this analysis, the suitability of three geographic levels—Lower Layer Super Output Areas (LSOAs), Middle Layer Super Output Areas (MSOAs), and Output Areas (OAs)—is thoroughly examined. Section 5.6 of the study presents a comprehensive evaluation and justification for selecting LSOAs as the preferred geographic level. This ensures both accurate geographic representation of cities and computational efficiency.

## 6.5 Intercity accessibility

The construction of HSR can improve the accessibility level of connected cities, but the integration level of HSR stations with other public transportation can change the total amount of benefit. Previous accessibility analyses of HSR usually focus on the inter-city travel time without considering the intra-city travel time to reach final destination from the HSR station. This section will examine the question of: How does the accessibility of the city change according to the integration level of station with public transport?

### 6.5.1 Service area delimitation

To incorporate access/egress time within the door-to-door framework, it is important to represent a city as an area rather than a single point. This allows for the consideration of varying access/egress times within the origin and destination cities. Consequently, it becomes necessary to delineate a service area from which a station attracts passengers. The literature offers several methods for defining the service area of a rail station, including buffer zones based on distance or time thresholds (Marti-Henneberg, 2015b), the use of administrative boundaries (Romero et al., 2021), assigning users to the nearest station (Blainey, 2010), and probabilistic station catchments (Young and Blainey, 2018). More detailed information on these methods is provided in Section 5.7.1.

The service area boundary for this study has been defined as the administrative boundary of the surrounding urban area, specifically the West Midlands County (Figure 6.5). It has seven metropolitan boroughs: the cities of Birmingham, Coventry and Wolverhampton, and the boroughs of Dudley, Sandwell, Solihull, and Walsall. Selecting the West Midlands as the service area boundary allows for a comprehensive and inclusive representation of the urban region surrounding the rail station. It considers the major cities and boroughs within the administrative boundary, which are likely to contribute a substantive portion of the station's passenger demand. West Midlands County comprises 1,718 origin centroids.

East Midlands and Greater London are selected as destination regions to evaluate how different scenarios impact the accessibility of the studied region to other areas (Figure 6.6). East Midlands comprises 616 destination centroids, while Greater London consists of 4,985 destination centroids across the region. Therefore, the journey time is computed from each of the 1,718 origins in West Midlands to all 616 destinations in East Midlands, and to all 4,985 destinations in Greater London, in order to reach the same destination centroids from all origin zones. Subsequently, the average journey time is calculated based on these computations.

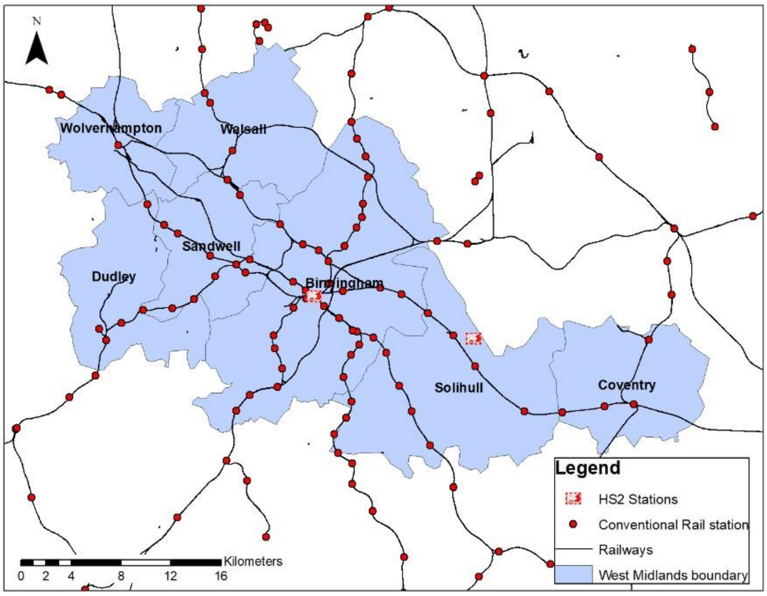


Figure 6.5 The boundary of origin region


Figure 6.6 The boundaries of destination regions

### 6.5.2 Spatial distribution of employment and population

The distributions of employment and population describe the distributions of possible passengers from three sorts of journeys, namely business, commute, and leisure trips. Business and commute trips are typically undertaken by individuals who are employed, whereas leisure trips can be taken by anyone. This distinction in passenger demographics helps to understand the varying travel patterns and demand for different trip purposes. The spatial distribution of employment has a direct impact on business and commute trips, and the spatial distribution of population has a direct impact on leisure trips.

The 2021 Census provides comprehensive data on various population characteristics and subjects areas, such as the number of usual residents in households and economic activity status (Office for National Statistics, 2023). The population considered in this analysis is based on the number of usual residents in households. The employment is based on the individuals who are aged 16 years and over and are considered economically active if they are employed.

It is important to note that employment data is categorised into two types: employment by residence and employment by workplace. The employment by residence metric refers to the number of people employed in a particular area based on where they live. On the other hand, employment by workplace reflects the number of people employed in a specific area based on where they work. In this analysis, employment by residence is used. The zoning systems used to categorise employment by workplace do not correspond with the population dataset utilised in this study. Integrating employment by workplace data would present significant challenges in terms of data harmonisation and interpretation.

Figure 6.7 shows how population and employment is spread across a geographical area. A higher population density is indicated with darker colours, and the same attribute is also for employment distribution. High populations are concentrated at Birmingham and Sandwell centre, but Birmingham centre has low employment. This can refer to two socio-economic dynamics. The first interpretation could be that a substantive proportion of the population commutes to work at locations outside of their residential region, indicating established commuter behaviour. Alternatively, such a pattern could show high levels of unemployment within the area. Moreover, Solihull has visible correlations between the population and employment distributions, areas with a high population density have high employment density, and correspondingly, low-density areas have less employment. The proposed HSR stations will provide great accessibility to population sites at city centres and employment sites at Solihull.

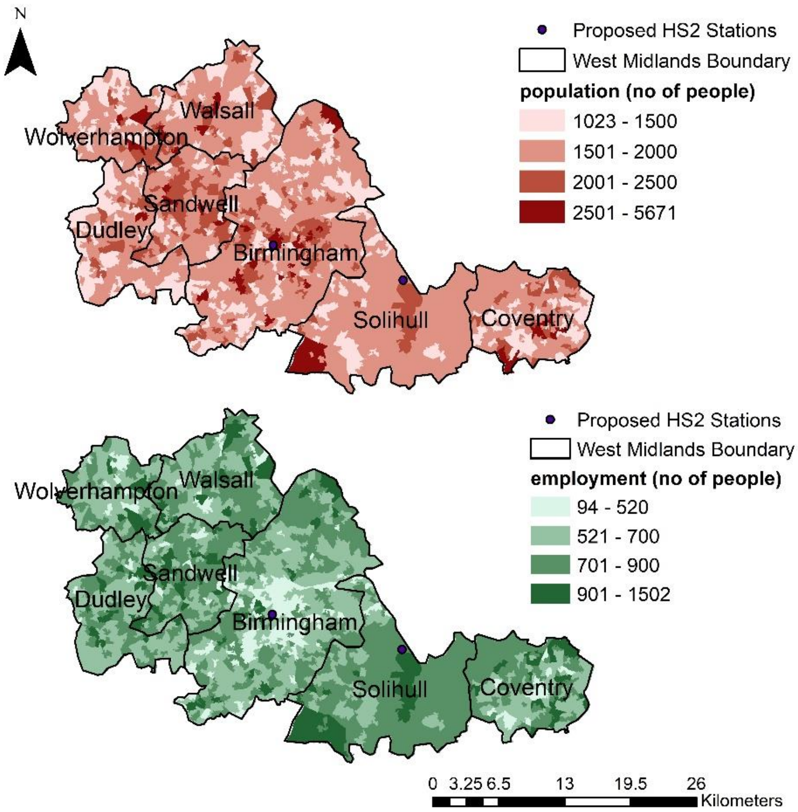


Figure 6.7 Population and employment distribution in West Midlands County

### 6.5.3 Station accessibility

This section concentrates on station accessibility, as the first step in accessing High-Speed Rail services. The simplest form of measuring accessibility is the cumulative measure, which involves summing up all the accessible population within a given time frame. This is a good approach to illustrate the differences of station accessibility level. The calculation has been carried out individually for different modes of transportation, encompassing public transport, buses, trains, cars, and walking.

The OTP surface analysis feature enables the creation of a catchment area around each station based on the travel time required to reach the station. Young, (2021) provides a tutorial paper on how to conduct this process. The surface analysis has a hard-coded cut-off of 120 minutes for the maximum extent of a surface. In this context, any centroids with more than 120 minutes or inaccessible, is assigned a value of 128. The proposed metro line extension, as mentioned in Section 6.4, for the Curzon Street station have been included before starting analysis.

It is important to ensure that the transportation modes used in the analysis accurately represent passenger behaviour. This entails modelling multi-modal public transportation routes that include rail, tram, bus, and pedestrian networks. In addition to multi-modal public transport journeys, it is also valuable to model trips that are restricted to specific modes, such as buses and walking, in order to capture more affordable travel options and private car journey which provides more journey start time flexibility. The line graph (see Figure 6.8) presents cumulative population by travel time from both New Street and Curzon Street train stations within the West Midlands region boundary.

Surprisingly, when considering all public transport modes for access, the populations reachable within a 60-minute time frame from New Street Station is consistently lower compared to that from Curzon Street Station. This shows that the public transport network around Curzon Street Station may have better coverage, more frequent service, or faster routes, allowing it to reach a larger population within the same time frame. However, beyond the 60-minute threshold, the cumulative population accessible from New Street Station exhibits better coverage compared to that from Curzon Street Station.

Specifically examining access by bus, across the given time frame, it is consistently observed that the population reachable from New Street Station is lower than that from Curzon Street Station. For access by car, it reaches a much larger population than the other modes for both stations, indicating that a larger portion of the population has quicker access to both train stations by car. It reaches nearly 2.8 million people around 80 minutes, and it doesn't grow beyond this point, showing that almost the entire population within study boundary can reach both train stations within 80 minutes of travel time by car. However, both stations have limited parking space available. New Street Station provides a short stay car parking facility with 39 spaces, and Curzon Street Station is also expected to offer limited short stay car parking options for rail users, as highlighted in the Curzon HS2 Master Plan (Birmingham City Council, 2015).

Considering access only by rail, the data shows a gradual increase in reachable population for both stations as the travel time increases. However, the rate of increase is consistently higher for New Street Station. At 60 minutes, the cumulative population that can be reached from Curzon Street Station is around 1.4 million people, whereas from New Street Station, it is significantly higher around 1.6 million people. For access by walking, Curzon Street Station consistently has a higher cumulative population reachable compared to New Street Station across the entire time range, though not much difference.

The analysis reveals that, as anticipated, the existing New Street station exhibits better connectivity with the existing rail network compared to Curzon Street station. Surprisingly, Curzon Street station demonstrates superior connectivity when considering car, bus, and on-foot access. However, when considering all public transport modes, a notable distinction emerges between the two stations. Before the 60-minute threshold, Curzon Street station demonstrates a more favourable trend, suggesting stronger connectivity for shorter journeys. Beyond the 60-minute threshold, the trend shifts, indicating that New Street station's connectivity becomes more prominent, possibly due to the impact of railway services facilitating longer access journeys.

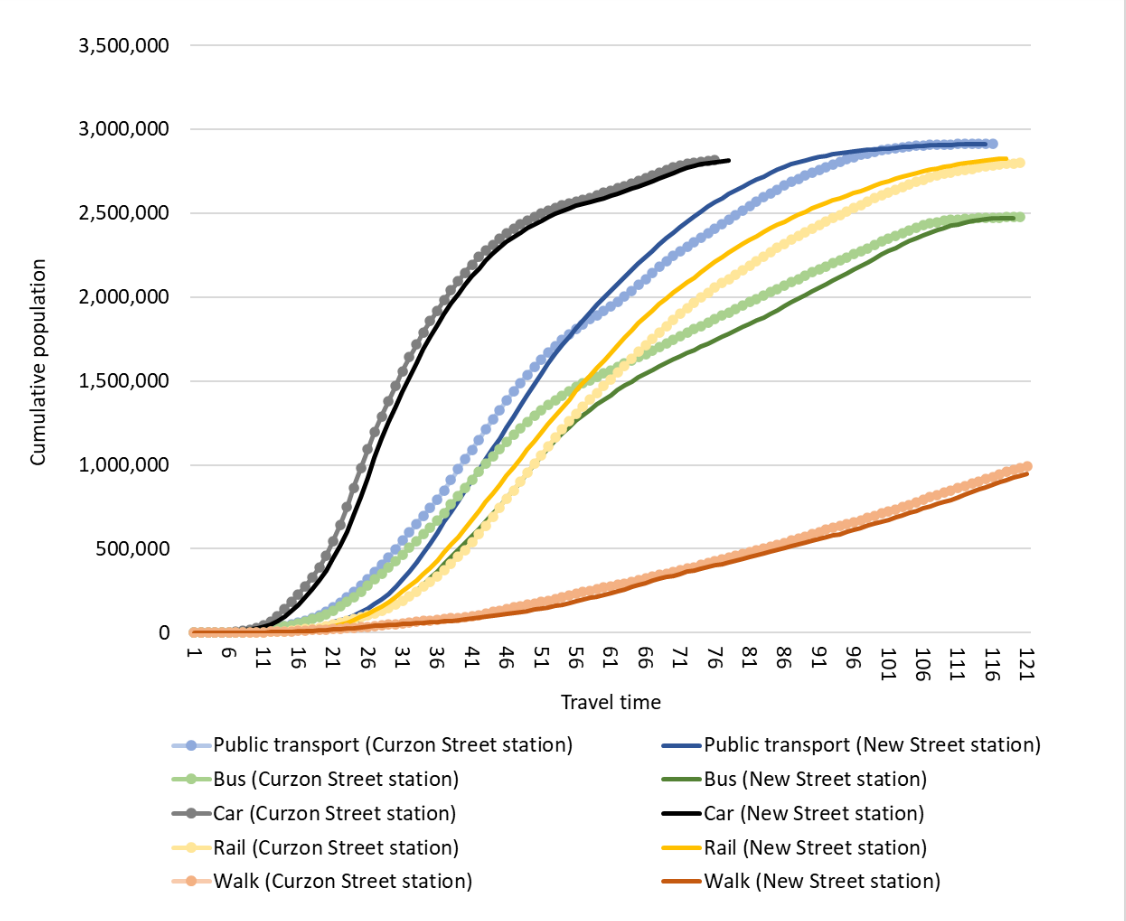


Figure 6.8 Cumulative population within travel time

Figure 6.9 shows the spatial distribution of journey times around the alternative HSR stations. The spatial variation does not exhibit substantive differences, except for two cases: when considering all public transport modes and the railway. Particularly, New Street Station is more accessible from the areas of Coventry, Wolverhampton, and Walsall. On the other hand, certain rail stations within the boundaries of Solihull and Dudley demonstrate better connectivity with Curzon Street station. To understand the reasons behind this case, an examination was conducted to determine the stations with which the railway lines are connected, see Figure 6.10. The Chiltern and Stratford railway lines pass through Birmingham Snow Hill, and Birmingham Moor Street stations in Birmingham, while all other lines to or through Birmingham use Birmingham New Street station as their main hub. Thus, transferring from Moor Street station to Curzon Street station on foot within a 3-minute timeframe is considerably more convenient than transferring to New Street station, which takes approximately 7 minutes. Overall, it can be concluded that West Midlands metropolitan county have better connectivity to New Street station. Therefore, when considering intercity accessibility in the subsequent analysis, the differences are expected to be particularly prominent around rail stations.

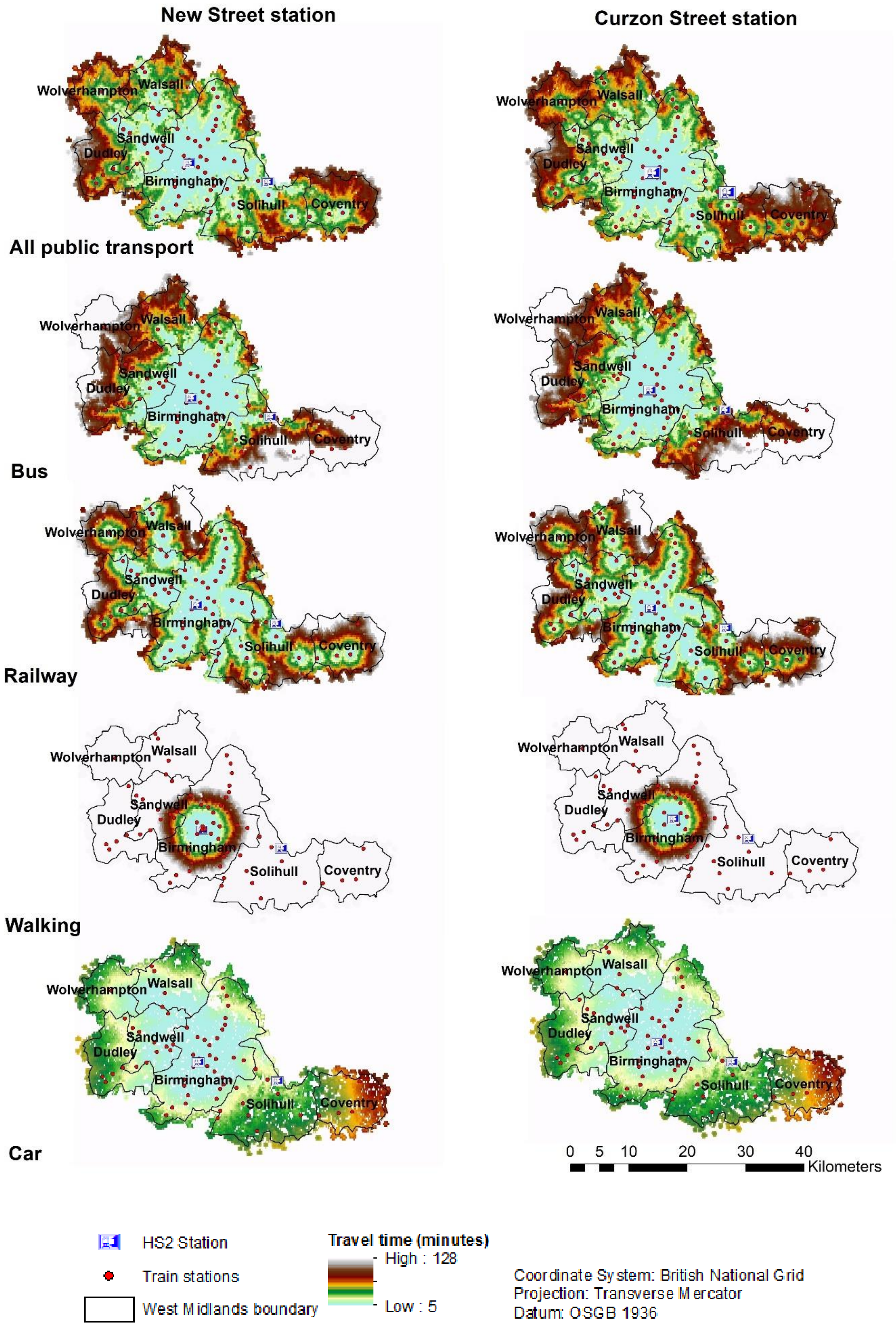


Figure 6.9 Access time variation around HSR stations within study boundary

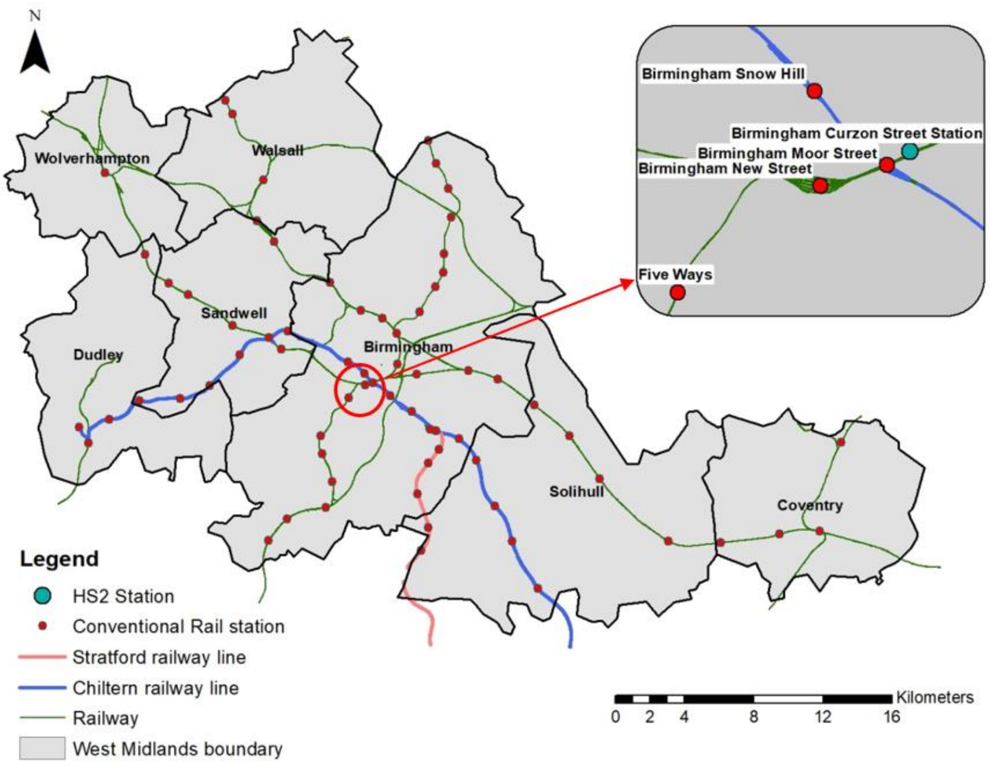


Figure 6.10 West Midlands County railway lines

### 6.5.4 Results

#### 6.5.4.1 Door-to-door journey time change

In this section, the outcomes of scenarios consisting of HSR stations with different levels of integration with other modes of transport is presented. The assessment focuses on how the accessibility of the study area to Greater London and the selected parts of the East Midlands is affected under two different scenarios. The study area (West Midlands) comprises 1,718 zones (origins), while Greater London and East Midlands as destination regions have 4,985 and 616 zones respectively. The construction of the HS2 project, whether in scenario 1 or scenario 2, can lead to improvements in accessibility. However, the extent of these improvements could differ across different areas. To find the spatial variation, journey times are computed from each of the 1,718 origins in West Midlands to all 616 destinations in East Midlands, and to all 4,985 destinations in Greater London, in order to reach the same destination centroids from all origin zones. Subsequently, the average journey time for each origin is calculated based on these computations. The spatial variation of total change in journey time (minutes), under the two HSR scenarios, to two specific regions: London and East Midlands (covering Derby and Nottingham) is presented below.

Passengers have the option to travel to their destination cities either via the HSR line, which offers shorter journey times on train and potentially improved accessibility or using the conventional network where travel times remain the same. The yellow zones indicate the areas with the least improvement in accessibility due to the construction of the HSR, showing that passengers in these zones may prefer to use conventional trains over HSR trains. On the other hand, the blue zones experience the greatest accessibility benefits from the new system, while the green zones have moderate benefits.

#### 6.5.4.1.1 To Greater London

In the base scenario, the station-to-station journey time from Birmingham (New Street station) to London (Euston station) is approximately 80 minutes. However, in the HS2 scenarios, where the departure station can be either Birmingham's New Street station or Curzon Street station, the station-to-station journey time between these two cities is reduced to 45 minutes.

Figure 6.11 shows the spatial variation of total change in journey time (minutes), under the two HSR scenarios, to London. Coventry does not experience benefits in terms of improved accessibility from either of the scenario options being considered. Coventry already has intercity services operating from Coventry station, which means that passengers would need to backtrack in order to access HS2 for travel to London. Passengers from Coventry may indeed prefer to use conventional trains while considering the potential advantages in terms of journey time. The borough of Solihull exhibits greater accessibility benefits in scenario 2. This means that this region likely has better connectivity with Curzon Street station compared to New Street station.

In the City of Birmingham, as well as in Wolverhampton and the borough of Sandwell, Scenario 1 demonstrates considerably greater accessibility benefits when compared to Scenario 2. On the contrary, the borough of Dudley seems to experience greater accessibility benefits under scenario 2 when compared to scenario 1. The higher benefits are generally observed around railway stations. This can be related to the fact that the railway line from these regions passes through Birmingham Snow Hill and Birmingham Moor Street stations, which offer more convenient accessibility to Curzon Street station. Figure 6.10 in Section 6.5.3 provides visual representation of this situation.

In the borough of Walsall, when examining the accessibility of bus and rail separately (see Figure 6.9 in Section 6.5.3), it becomes apparent that the east side of the region experiences greater accessibility benefits from the railway connection, resulting in improved access to New Street station. In contrast, the west side relies predominantly on the bus network, making Curzon Street station more accessible from that direction. In Scenario 1, accessibility is primarily supported by the rail network, leading to improved access to New Street station. Conversely, in Scenario 2, the bus network plays a more prominent role in enhancing accessibility. These differences in scenarios highlight the contrasting influence of rail and bus networks on accessibility, with the eastern part benefiting from the existing railway line and the western part benefiting from the advantages of the bus network.

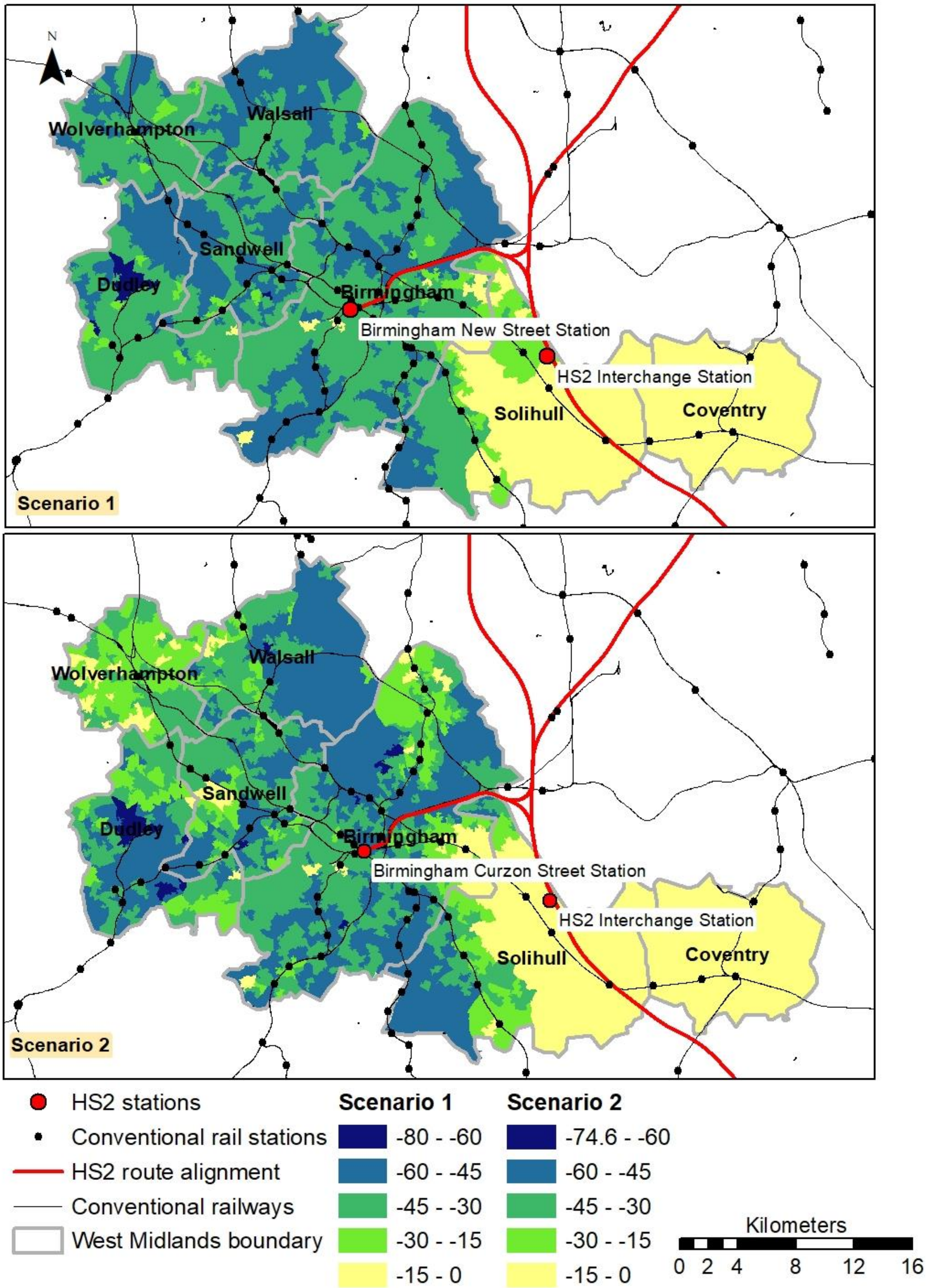


Figure 6.11 D2D journey time (minutes) change to London per zones

Figure 6.12 shows the spatial distribution of total journey time from West Midlands to London. The x-axis represents different journey time ranges, and the y-axis represents the frequency. In the base case, the total journey time range spans from 120 to 280 minutes. However, this range for scenarios falls within the 95 to 235 minutes duration. Notably, the journey time range of 190-200 minutes exhibits a high frequency, occurring 329 times. In both Scenario 1 and Scenario 2, there is a prominent peak in the journey time range of 155-165 minutes. This peak is significant, with a frequency of 455 in Scenario 1 and 424 in Scenario 2. These high frequencies show that a substantial number of journeys took around 155-165 minutes. Furthermore, both scenarios demonstrate lower frequencies for journey time ranges below 135 minutes and above 205 minutes. This implies that fewer journeys fell into those duration ranges. This insight from the histogram helps understand the common journey durations and the distribution of travel times for this specific route.

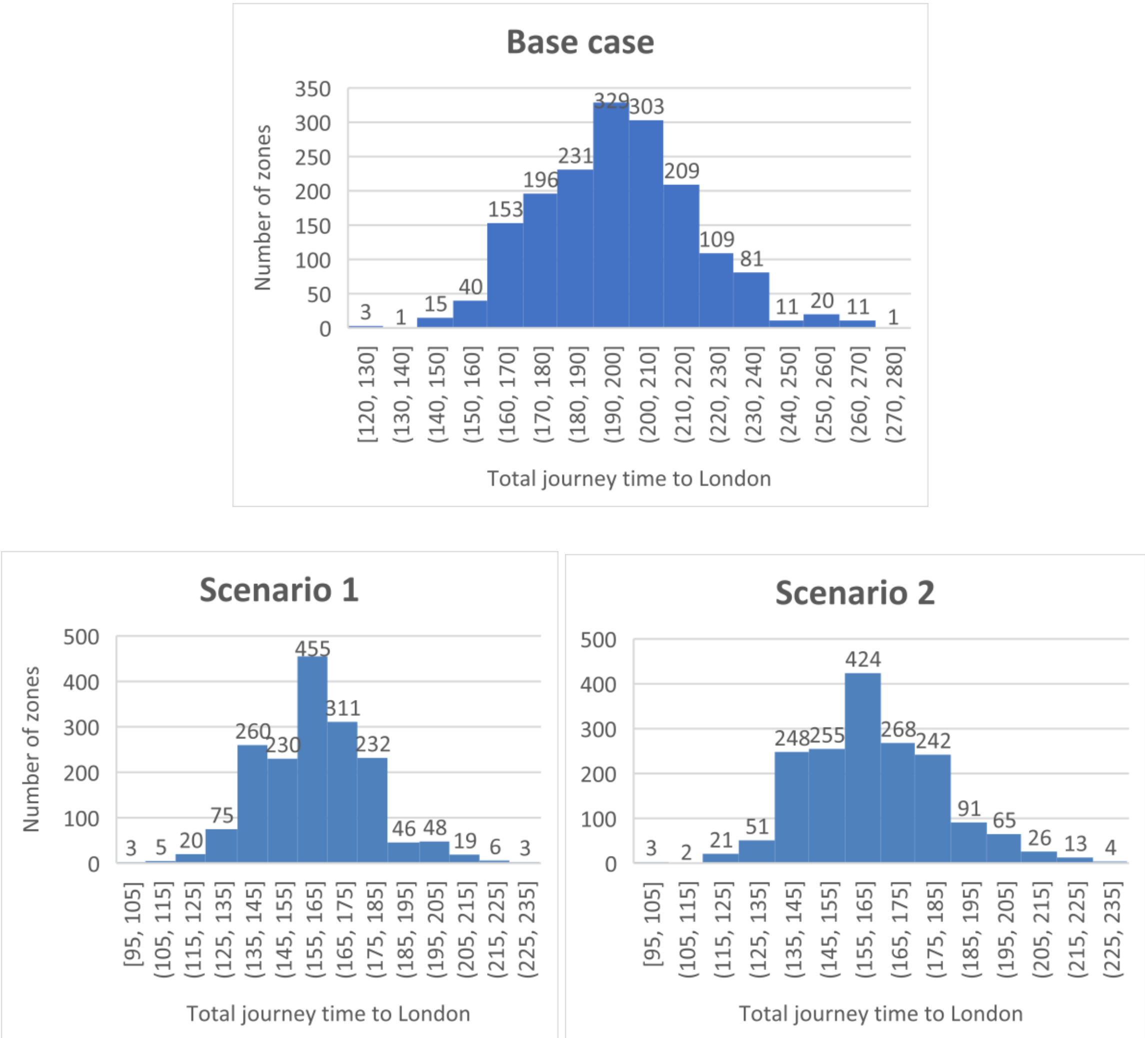


Figure 6.12 Spatial distribution of D2D journey time

Moreover, Figure 6.13 illustrates the total journey time across different time periods—7:00 am, 11:00 am, and 5:00 pm—for both the base case and two scenarios. Public transit networks frequently modify their service frequencies depending on the time of day. For example, during rush hours like 7:00 am and 5:00 pm, when commuters are commuting to and from work, transit services may increase their frequency to meet the heightened demand. This adjustment can lead to reduced wait times and quicker overall travel times. Conversely, during non-peak hours such as 11:00 am, service frequencies might decrease, resulting in extended wait times and possibly slower travel times.

Interestingly, there is minimal temporal variation across all scenarios. In the base case, Birmingham, Solihull, and Coventry exhibit slightly higher accessibility at 07:00 am. However, in Scenario 1, Walsall demonstrates higher accessibility at 11:00, while Dudley experiences the lowest accessibility at 07:00. Conversely, Solihull exhibits lower accessibility at 17:00 compared to other journey times. In Scenario 2, Walsall shows higher accessibility at 11:00, whereas Solihull and Birmingham exhibit higher accessibility at 07:00.

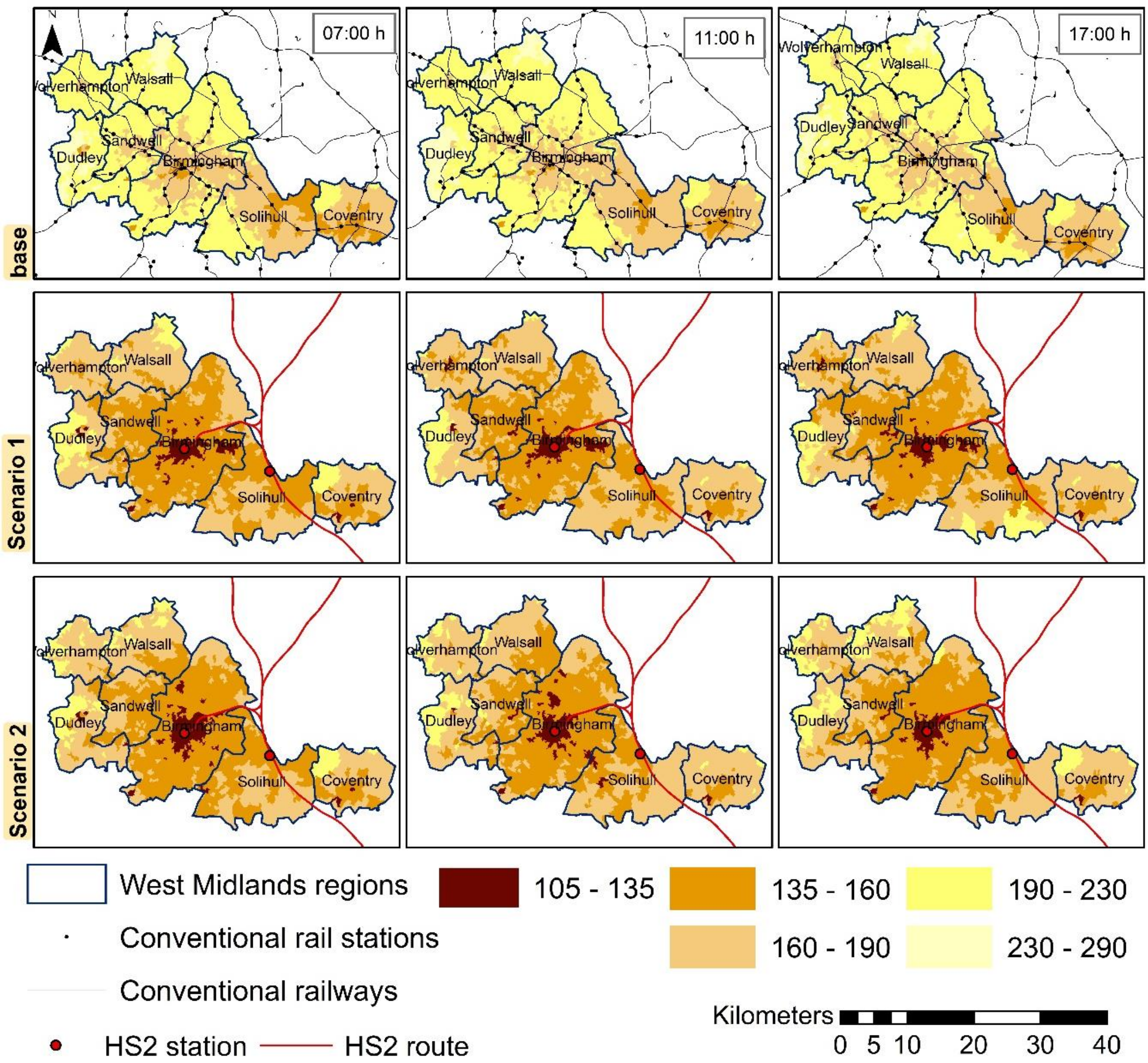


Figure 6.13 Temporal variation of spatial distiribution of total journey time to London

Table 6.2 presents the cumulative percentage of the population and employment within different total travel time thresholds to London for the base scenario, Scenario 1, and Scenario 2. The introduction of either Scenario 1 or Scenario 2 in the context of the HS2 project can lead to improvements in accessibility. However, the differences in cumulative percentages between Scenario 1 and Scenario 2 are relatively minor.

At a total travel time threshold of 150 minutes, there are minimal differences between the two scenarios. Scenario 1 has a cumulative percentage of 27.0% of the population, while Scenario 2 has a slightly lower percentage of 26.2%. Similarly, for employment, Scenario 1 has a cumulative percentage of 23.5%, while Scenario 2 has a slightly lower percentage of 22.6%. These differences are relatively small, indicating a similar distribution of population and employment within this travel time threshold in both scenarios. However, as observing the map above, different regions within the area experience distinct benefit under the two scenarios. This implies that there may be specific reasons why one scenario is preferred over the other, such as improved accessibility for more remote areas or other location-based advantages.

As the total travel time threshold increases to 180 minutes, the cumulative percentages rise further for both Scenario 1 and Scenario 2. In Scenario 1, the cumulative percentage of the population and employment is 86.3% and 85.0%, respectively. In Scenario 2, it is slightly lower, with a cumulative percentage of 81.2% for the population and 79.8% for employment. Although the differences between the two scenarios have slightly increased, they are still not substantial. These findings show that, overall, the differences in cumulative percentages between Scenario 1 and Scenario 2 are not substantial. Both scenarios show a similar trend, with a gradual increase in the cumulative percentages as the total travel time threshold to London increases.

Table 6.2 Cumulative percentage of population and employment within different D2D journey time thresholds to London

| | PERCENTAGE OF POPULATION (%) | | | PERCENTAGE OF EMPLOYMENT (%) | | |
|---|---|---|---|---|---|---|
| **TIME (MIN)** | **Base** | **Scenario 1** | **Scenario 2** | **Base** | **Scenario 1** | **Scenario 2** |
| **120** | 0.3 | 1.0 | 1.3 | 0.3 | 1.1 | 1.1 |
| **150** | 1.3 | 27.0 | 26.2 | 1.2 | 23.5 | 22.6 |
| **180** | 24.6 | 86.3 | 81.2 | 23.1 | 85.0 | 79.8 |
| **210** | 74.7 | 99.3 | 98.6 | 73.0 | 99.2 | 98.4 |
| **240** | 97.6 | 100.0 | 100.0 | 97.4 | 100.0 | 100.0 |
| **300** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 6.3 presents a statistical evaluation of journey stages to London, looking at different time components of a typical journey under different scenarios, including a base case and two alternative scenarios. The time components include access time, waiting time, transfer time, in-vehicle time, egress time, and door-to-door time. For each of these time components and

scenarios, the table provides mean (average) values, standard deviations (sd), and their relative percentage contribution to the total D2D time.

Access time is the time spent on initial public transit or walking to the rail station. In Scenario 1, there is almost no differences in the average access time compared to the Base case. In Scenario 2, however, the average access time increases from 31.33 to 36.39 minutes, which could mean a decrease in accessibility. However, a slightly longer access journey to Curzon Street provides the advantage of accessing HSR services directly to London, rather than maintaining a shorter access journey to New Street and then transferring to a non-HSR train for the London journey. Also, the sd increases to 18.16 minutes, meaning a larger variability in access times among passengers. Waiting time does not show substantive differences for both scenarios. Base case, Scenario 1 and Scenario 2 are 8.19 minutes, 7.57 and 9.21 minutes, respectively.

Transfer time refers to the duration between transferring from one train to another during a journey that involves multiple train connections. In Scenario 1, the transfer time is similar to the base case, indicating that the transfer system remains unchanged. However, in Scenario 2, the transfer time slightly decreases to 7.09 minutes. This shows that Scenario 2 may have a more efficient transfer system in place or reduce the need for multiple transfers.

In-vehicle time refers to total duration spent inside the train while travelling from the origin station to the destination station. There is a substantive decrease in the average in-vehicle time in both Scenarios 1 and 2 compared to the Base case (from 97.46 minutes to 63.05 and 60.54 minutes, respectively). However, Scenarios 1 and 2 show similar decreases in average in-vehicle time.

The egress time, which refers to the duration required for passengers to exit the train station and then reach their destination, appears to exhibit a similar condition across all scenarios. This consistency could be attributed to the fact that the destination station for all scenarios is London Euston. Therefore, regardless of the specific changes or variations in the scenarios, the egress time remains similar due to the common endpoint.

Table 6.3 Statistical evaluation of journey time stages to London

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Access time** | **Waiting time** | **Transfer time** | **In-vehicle time** | **Egress time** | **D2D time** |
| **Base case** | mean | 31.33 | 8.19 | 10.03 | 97.46 | 41.66 | 196.28 |
| | sd | 15.4 | 6.35 | 7.97 | 17.22 | 2.97 | 24.64 |
| | percentage | 17% | 5% | 6% | 50% | 22% | 100% |
| **Scenario 1** | mean | 30.9 | 7.57 | 10.56 | 63.05 | 41.52 | 160.95 |
| | sd | 15.78 | 6.06 | 7.84 | 10.91 | 2.68 | 20.2 |
| | percentage | 20% | 6% | 8% | 39% | 27% | 100% |
| **Scenario 2** | mean | 36.39 | 9.21 | 7.09 | 60.54 | 41.32 | 162.77 |
| | sd | 18.16 | 5.96 | 6.29 | 12.13 | 2.79 | 21.25 |
| | percentage | 23% | 7% | 5% | 37% | 26% | 100% |
| *sd: standard deviation* | | | | | | | |

Additionally, one-way ANOVA analysis is conducted to determine if the means of these three scenarios are significantly different from each other. ANOVA gives result if there are differences among group means, but not what the differences are. To find out which groups are statistically different from one another, a Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc test for pairwise comparisons was performed. The Table 6.4 shows the results of the one-way ANOVA along with the Tukey post-hoc multiple comparisons. A one-way ANOVA revealed that there is a statistically significant difference in the mean of three scenarios between at least two groups ($F (2, 5151) = [1391], p = 0.000$). Tukey post hoc test for multiple comparisons found that there are statistically significant differences ($p < 0.05$) between Base scenario and Scenario 1, Base scenario and Scenario 2, Scenario 1 and Scenario 2.

Table 6.4 One-way ANOVA results and Tukey Post-hoc test comparison

| | **Sum of Squares** | **Df** | **Mean Square** | **F** | **Sig.** | **Differences** |
|---|---|---|---|---|---|---|
| **Between Groups** | 1359988 | 2 | 679994 | 1391 | 0.000 | Base – Scenario 1<br>Base – Scenario 2<br>Scenario 1 – Scenario 2 |
| **Within Groups** | 2518463 | 5151 | 489 | | | |
| **Total** | 3878451 | 5153 | | | | |

It is widely recognised that passengers do not perceive all stages of the journey in the same way (Martin, 1997). Therefore, applying weighted factors helps to capture and describe the traveller's perspective for each specific stage. In this context, as discussed in Chapter 3, Section 3.4, based on the study of Román et al., (2014), the assigned weighted factors are as follows: an importance factor of 1.25 is attributed to both access and egress times. This indicates that these stages carry relatively higher significance from the traveller's point of view compared to in-vehicle time. Furthermore, a weighted factor of 2.6 is assigned to both waiting time and transfer time, signifying that these stages have an even greater impact on the overall perception of the journey.

Table 6.5 presents the results with weighted factors that consider the traveller's perspective for each stage of the journey.

The percentage indicates the relative contribution of each stage to the total D2D time. When considering weighted factors, the analysis demonstrates a noticeable change in the relative contribution of each journey stage, highlighting the increased impact of out-of-vehicle time (access, egress, waiting, and transfer time) and a decrease in the contribution of in-vehicle time.

In Scenario 1, the non-weighted analysis showed that waiting time and transfer time contributed 6% and 8% respectively. However, when considering the weighted factors, these contributions increased to 10% and 14% respectively. On the other hand, the contribution of access time, in-vehicle time and egress time decreased from 20%, 39% and 27% to 19%, 31% and 26% when weighted.

In Scenario 2, the non-weighted analysis showed that waiting time and transfer time contributed 7% and 5% respectively. However, when considering the weighted factors, these contributions increased to 12% and 9% respectively. On the other hand, the contribution of in-vehicle time decreased from 37% to 30% when weighted. The access and egress time stayed on the same percentage, 23% and 26%.

Table 6.5 Statistical evaluation of generalised journey time stages to London

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **W. access time** | **W. waiting time** | **W. transfer time** | **W. in-vehicle time** | **W. egress time** | **W. D2D time** |
| **Base case** | mean | 39.16 | 21.29 | 26.07 | 97.46 | 52.07 | 236.05 |
| | sd | 19.25 | 16.51 | 20.73 | 17.22 | 3.71 | 34.02 |
| | percentage | *17%* | *9%* | *11%* | *41%* | *22%* | *100%* |
| **Scenario 1** | mean | 38.63 | 19.68 | 27.46 | 63.05 | 51.90 | 200.73 |
| | sd | 19.72 | 15.76 | 20.37 | 10.91 | 3.35 | 29.37 |
| | percentage | *19%* | *10%* | *14%* | *31%* | *26%* | *100%* |
| **Scenario 2** | mean | 45.48 | 23.94 | 18.44 | 60.54 | 51.65 | 200.05 |
| | sd | 22.70 | 15.49 | 16.35 | 12.13 | 3.48 | 28.15 |
| | percentage | *23%* | *12%* | *9%* | *30%* | *26%* | *100%* |
| *sd: standard deviation* | | | | | | | |

The meta-study conducted by Wardman et al. (2016) revealed that for inter-urban journeys, access time has a multiplier of 1.9, while wait time has a multiplier of 1.5. This indicates that waiting time has less impact than access time, in contrast to the findings of Román et al. (2014). Further details on this comparison can be found in Section 3.4. Figure 6.14 shows a comparison of average generalised journey time components across all zones in the study area based on findings of both studies. Three distinct shapes represent different scenarios, while colours show the values for different journey time components. Access and egress time increased in the range of 20-30 minutes, while waiting and transfer time decreased in the range of 5-15 minutes. The change in D2D journey time reflects the overall impact of varying weight values, which have increased across all scenarios. The Wardman GJT times lead to an increase in average D2D journey time. However, since this increase is consistent across all scenarios, so is unlikely to have a substantial impact on which scenario is the 'best' option.

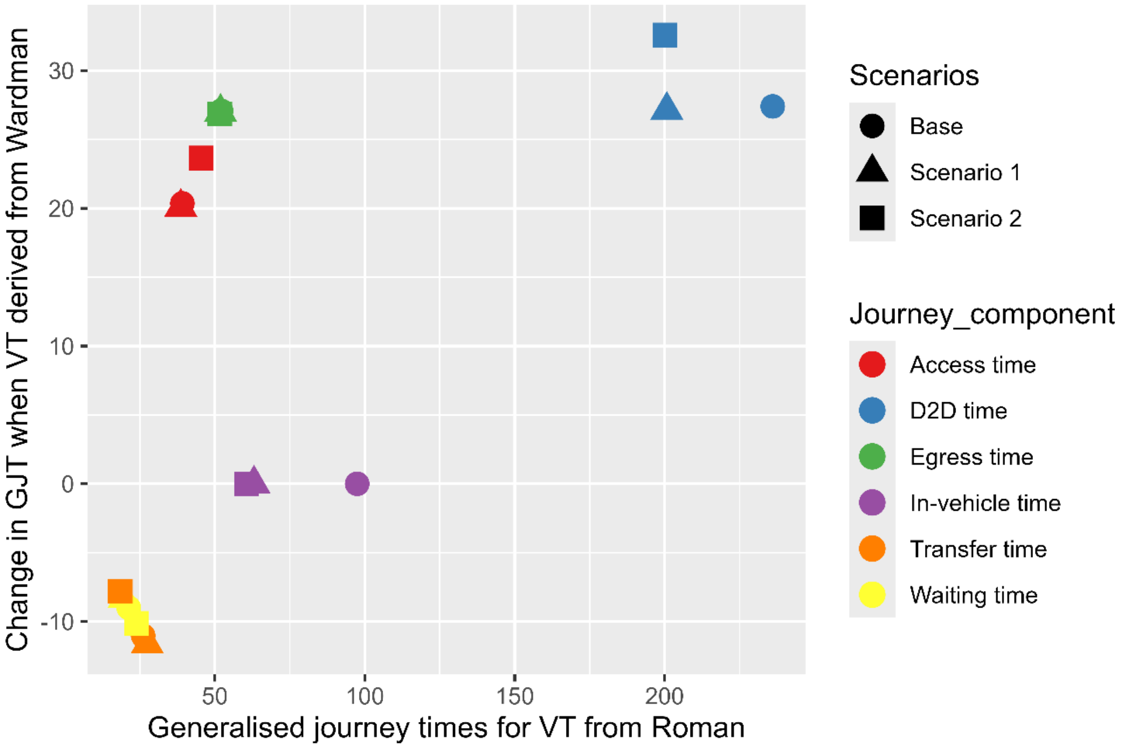


Figure 6.14 Comparison of generalised journey time components for different values of time

### 6.5.4.1.2 To East Midlands

In the base scenario, the station-to-station journey time from Birmingham (New Street station) to Derby and Nottingham are approximately 40 and 60 minutes respectively. However, in the HS2 scenarios, the station-to-station journey time from either Birmingham's New Street station or Curzon Street station to East Midlands Hub is reduced to 30 minutes.

Figure 6.15 shows the spatial variation of total change in journey time (minutes), under the two HSR scenarios, to East Midlands. The West Midlands to East Midlands corridor displays notable disparities in accessibility when compared to the West Midlands to London corridor. For example, the borough of Coventry demonstrates a higher level of accessibility change in scenario 1, meaning that this region likely has better connectivity with New Street station compared to Curzon Street station.

The accessibility pattern in other metropolitan areas aligns with that of the West Midlands to London corridor. In Scenario 2, the boroughs of Solihull and Dudley exhibit higher accessibility benefits. Similarly, Scenario 1 demonstrates significantly greater accessibility advantages in the cities of Birmingham, Wolverhampton, and the borough of Sandwell. However, in the borough of Walsall, it remains challenging to determine which scenario offers higher accessibility. This might relate to fact that the eastern side of Walsall benefits more from the railway connection, improving access to New Street station, while the western side relies on the bus network, enhancing accessibility to Curzon Street station. Figure 6.9 in Section 6.5 illustrates the spatial variation in accessibility resulting from the utilisation of different transport modes.

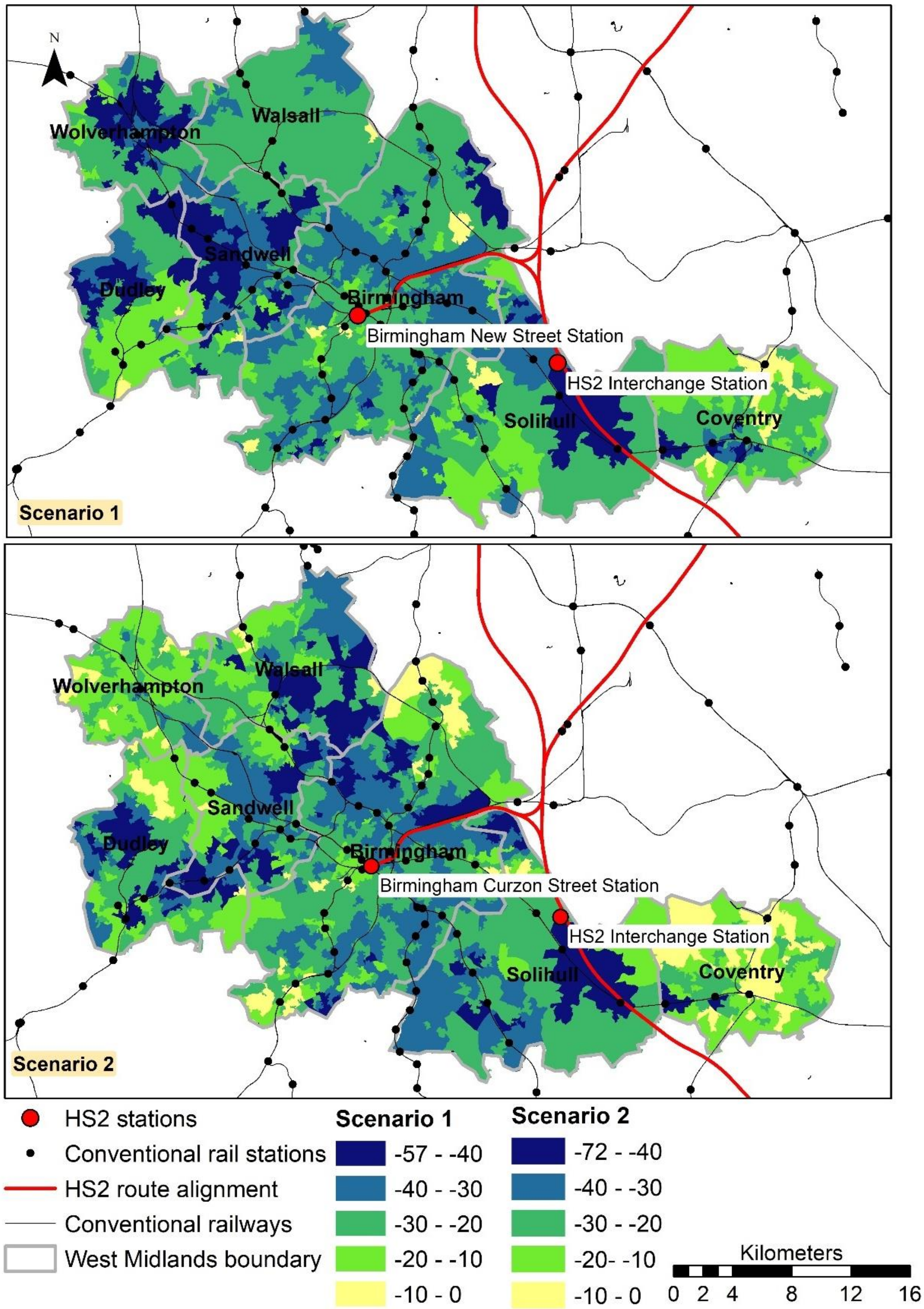


Figure 6.15 D2D journey time (minutes) change to East Midlands per zones

Figure 6.16 shows the spatial distribution of total journey time from West Midlands to East Midlands. In the base case, the total journey time range spans from 104 to 244 minutes. However, this range for scenarios falls within the 83 to 203 minutes duration. Notably, the journey time range of 144-154 minutes exhibits a high frequency, occurring 424 times. In both scenario 1 and scenario 2, the highest frequency occurs within the 113-123 minutes interval. However, there are intervals in scenario 2 where the frequency is greater compared to scenario 1. These intervals are

133-143 minutes and 163-173 minutes. Conversely, scenario 1 exhibits a higher frequency for the 103-113 minute and 123–133 minutes intervals. This information highlights the differences in journey times between the two scenarios.

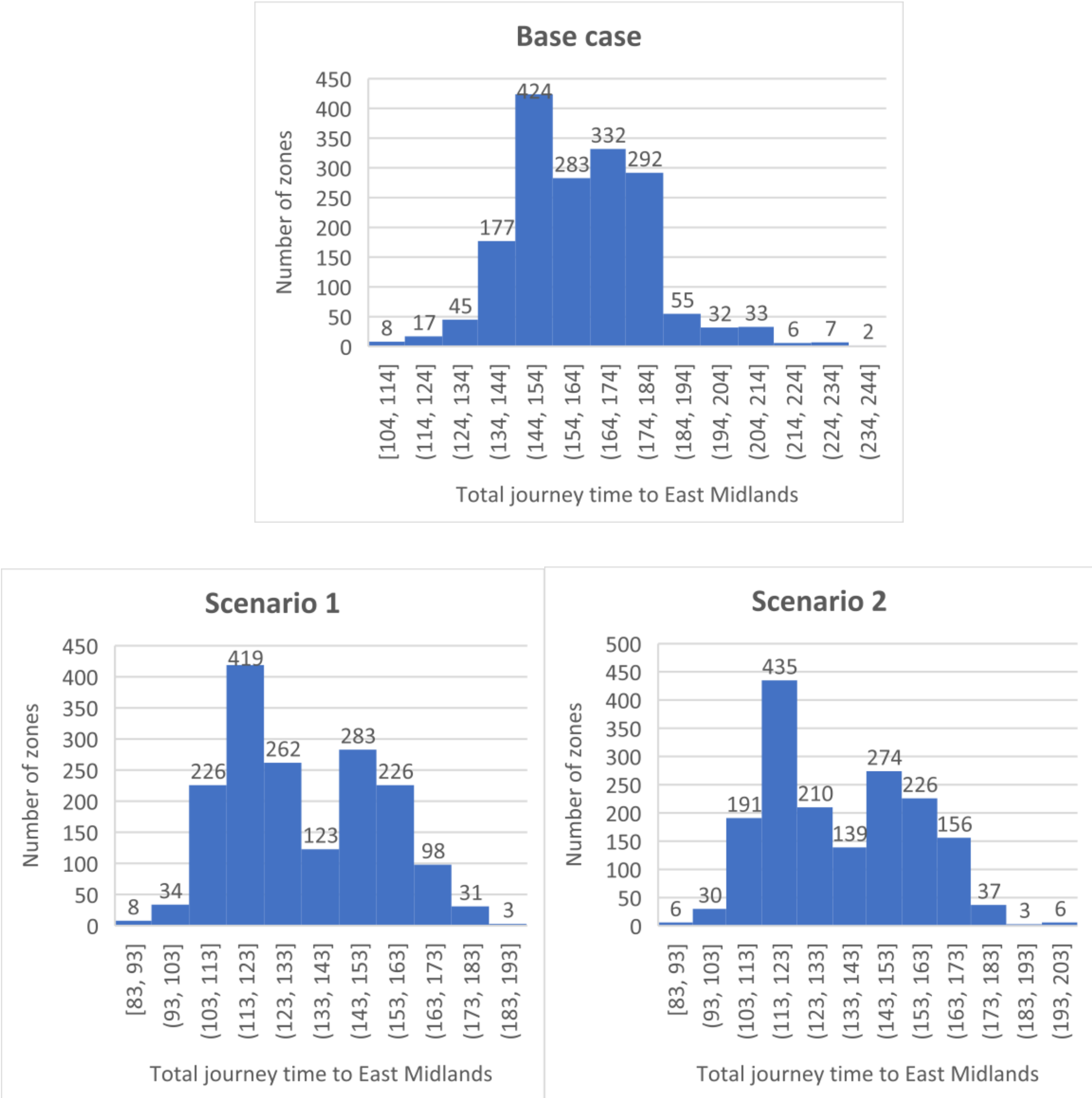


Figure 6.16 Spatial distribution of total journey time

Figure 6.17 illustrates the total journey time across different time periods—7:00 am, 11:00 am, and 5:00 pm—for both the base case and two scenarios. In the base case, temporal variation remains minimal. However, in Scenario 1, Birmingham, Sandwell, and Solihull show decreased accessibility at 07:00 am. Similarly, in Scenario 2, these areas also display reduced accessibility at 07:00 am. conversely, Walsall and Dudley exhibit heightened accessibility at 11:00, potentially indicating improved transport efficiency during mid-morning hours. Interestingly, Wolverhampton experiences decreased accessibility at 17:00.

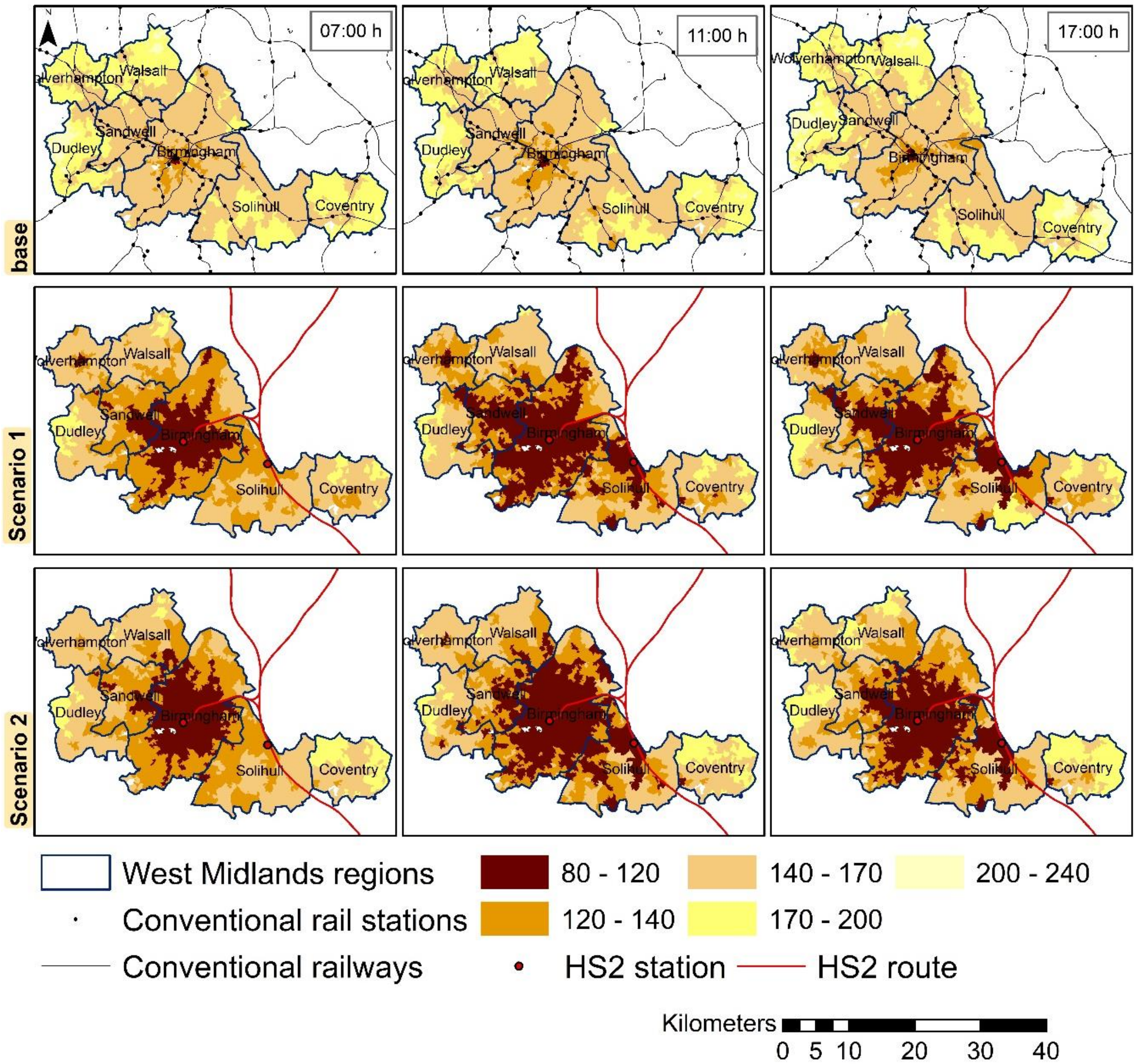


Figure 6.17 Temporal variation of spatial distribution of total journey time to East Midlands

Table 6.6 presents the cumulative percentage of the population and employment within different total travel time thresholds to East Midlands. The implementation of either Scenario 1 or Scenario 2 within the context of the HS2 project has the potential to enhance accessibility significantly. At a 120-minute time threshold, the base scenario covers 1.3% of the population. However, in Scenario 1 and Scenario 2, this percentage significantly rises to 33.7% and 33.2%, respectively. As the time threshold increases to 150 minutes, the base scenario reaches 33.6% of the population, while Scenario 1 and Scenario 2 show higher percentages of 75.2% and 71.6%, respectively. When considering accessibility, both scenarios exhibit similar overall outcomes with only slight variations in performance. However, it is important to note that these results are observed at an aggregate level, and it does not necessarily mean that the same population benefits in each scenario compared to the base scenario.

Table 6.6 Cumulative percentage of population and employment within different total travel time thresholds to East Midlands

| | PERCENTAGE OF POPULATION (%) | | | PERCENTAGE OF EMPLOYMENT (%) | | |
|---|---|---|---|---|---|---|
| **TIME (MIN)** | **Base** | **Scenario 1** | **Scenario 2** | **Base** | **Scenario 1** | **Scenario 2** |
| **90** | 0.3 | 0.5 | 0.4 | 0.3 | 0.6 | 0.5 |
| **120** | 1.3 | 33.7 | 33.2 | 1.3 | 30.6 | 30.2 |
| **150** | 33.6 | 75.2 | 71.6 | 30.4 | 73.4 | 70.0 |
| **180** | 88.9 | 99.7 | 99.2 | 87.8 | 99.7 | 99.1 |
| **210** | 98.7 | 100.0 | 100.0 | 98.5 | 100.0 | 100.0 |
| **240** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 6.7 summarises the statistical evaluation of journey stages to East Midlands. In Scenario 1, there is almost no differences in the average access time compared to the Base case. In Scenario 2, however, the access time increases from 29.51 to 33.04 minutes, which could mean a decrease in accessibility. Additionally, the standard deviation increases to 15.82 minutes, meaning a larger variability in access times among passengers. Waiting time does not show substantive differences for both scenarios. Base case, Scenario 1 and Scenario 2 are 6.98 minutes, 6.66 and 7.86 minutes, respectively.

In Scenario 1, the transfer time is similar to the base case, indicating that the transfer system remains unchanged. On the other hand, in Scenario 2, there is a slight reduction in transfer time to 11.98 minutes. This shows that Scenario 2 may have a more efficient transfer system in place or a reduced need for frequent transfers. Both Scenarios 1 and 2 demonstrate a notable decrease in average in-vehicle time when compared to the Base case. The average in-vehicle time significantly decreases from 65.36 minutes in the Base case to 38.96 minutes in Scenario 1 and 38.15 minutes in Scenario 2. However, both scenarios exhibit similar reductions in average in-vehicle time.

Table 6.7 Statistical evaluation of journey stages to East Midlands

| | STATISTICAL EVALUATION OF JOURNEY STAGE | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Access time** | **Waiting time** | **Transfer time** | **In-vehicle time** | **Egress time** | **D2D time** |
| **Base case** | mean | 29.51 | 6.98 | 14.42 | 65.36 | 36.32 | 153.77 |
| | sd | 14.88 | 5.71 | 10.10 | 17.70 | 8.39 | 29.01 |
| | percentage | 19% | 5% | 9% | 43% | 24% | 100% |
| **Scenario 1** | mean | 28.79 | 6.66 | 14.89 | 38.96 | 36.43 | 126.90 |
| | sd | 14.49 | 5.14 | 7.97 | 12.20 | 8.84 | 26.87 |
| | percentage | 23% | 5% | 12% | 31% | 29% | 100% |
| **Scenario 2** | mean | 33.04 | 7.86 | 11.98 | 38.15 | 36.09 | 129.26 |
| | sd | 15.82 | 4.96 | 6.55 | 14.03 | 8.60 | 28.46 |
| | percentage | 26% | 6% | 9% | 30% | 29% | 100% |
| *sd: standard deviation* | | | | | | | |

In addition, a one-way ANOVA analysis is conducted to assess whether there are significant differences among the means of three scenarios. The ANOVA test indicated that there is indeed a statistically significant difference in the mean values of the scenarios ($F (2, 5151) = [925.1]$, $p = 0.000$). However, ANOVA alone does not specify which specific groups exhibit significant differences. To determine the pairwise differences between groups, a Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc test is performed. The results of the Tukey post-hoc test revealed statistically significant differences ($p < 0.05$) between the Base scenario and Scenario 1, between the Base scenario and Scenario 2, as well as between Scenario 1 and Scenario 2. The Table 6.8 shows the results of the one-way ANOVA along with the Tukey post-hoc multiple comparisons.

Table 6.8 One-way ANOVA results and Tukey Post-hoc test comparison

| | **Sum of Squares** | **Df** | **Mean Square** | **F** | **Sig.** | **Differences** |
|---|---|---|---|---|---|---|
| **Between Groups** | 832474 | 2 | 416237 | 925.1 | 0.000 | Base – Scenario 1<br>Base – Scenario 2<br>Scenario 1 – Scenario 2 |
| **Within Groups** | 2317700 | 5151 | 450 | | | |
| **Total** | 3150174 | 5153 | | | | |

Table 6.9 presents the results with weighted factors that consider the traveller's perspective for each stage of the journey. The percentage indicates the relative contribution of each stage to the total D2D time. When considering weighted factors, the analysis demonstrates a noticeable change in the relative contribution of each journey stage, highlighting the increased impact of out-of-vehicle time (access, egress, waiting, and transfer time) and a decrease in the contribution of in-vehicle time.

In Scenario 1, the non-weighted analysis showed that waiting time and transfer time contributed 5% and 12%, respectively. However, when considering the weighted factors, these contributions increased to 10% and 22% respectively. On the other hand, the contribution of access time, in-vehicle time and egress time decreased from 23%, 31% and 29% to 20%, 22% and 26% when weighted.

In Scenario 2, the non-weighted analysis showed that waiting time and transfer time contributed 6% and 9%, respectively. However, when considering the weighted factors, these contributions increased to 12%, and 18% respectively. On the other hand, the contribution of access time, in-vehicle time and egress time decreased from 26%, 30% and 29% to 23%, 22% and 26% when weighted.

Table 6.9 Statistical evaluation of generalised journey time stages to East Midlands

| STATISTICAL EVALUATION OF JOURNEY STAGES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **W. access time** | **W. waiting time** | **W. transfer time** | **W. in-vehicle time** | **W. egress time** | **W. D2D time** |
| **Base case** | mean | 36.88 | 18.15 | 37.50 | 65.36 | 45.41 | 203.30 |
| | sd | 18.60 | 14.84 | 26.25 | 17.70 | 10.49 | 44.11 |
| | percentage | *18%* | *9%* | *18%* | *32%* | *22%* | *100%* |
| **Scenario 1** | mean | 35.99 | 17.31 | 38.70 | 38.96 | 45.54 | 176.51 |
| | sd | 18.11 | 13.38 | 20.73 | 12.20 | 11.05 | 38.85 |
| | percentage | *20%* | *10%* | *22%* | *22%* | *26%* | *100%* |
| **Scenario 2** | mean | 41.30 | 20.43 | 31.15 | 38.15 | 45.11 | 176.15 |
| | sd | 19.78 | 12.88 | 17.02 | 14.03 | 10.75 | 38.39 |
| | percentage | *23%* | *12%* | *18%* | *22%* | *26%* | *100%* |
| ***sd: standard deviation*** | | | | | | | |

Wardman et al. (2016) conducted a meta-analysis indicating that access time is given a multiplier of 1.9, while wait time is assigned a multiplier of 1.5 for inter-urban travels. This suggests that access time has a greater impact compared to wait time, which differs from the findings of Román et al. (2014). More detailed comparison is provided in Section 3.4. In Figure 6.18, a comparison of average generalised journey time components across all zones in the study area based on both studies is illustrated. The figure displays three distinct shapes representing different scenarios, with colours indicating values for different journey time components.

Access and egress time show an increase within the 15-25 minutes range, while waiting and transfer time exhibit a decrease ranging from 5-15 minutes. The change in door-to-door (D2D) journey time reflects the collective influence of varying weight values, which have risen across all scenarios. Wardman's generalised journey time values led to an increase in average D2D journey time. However, since this increase is consistent across all scenarios, it is unlikely to significantly impact the determination of the optimal scenario.

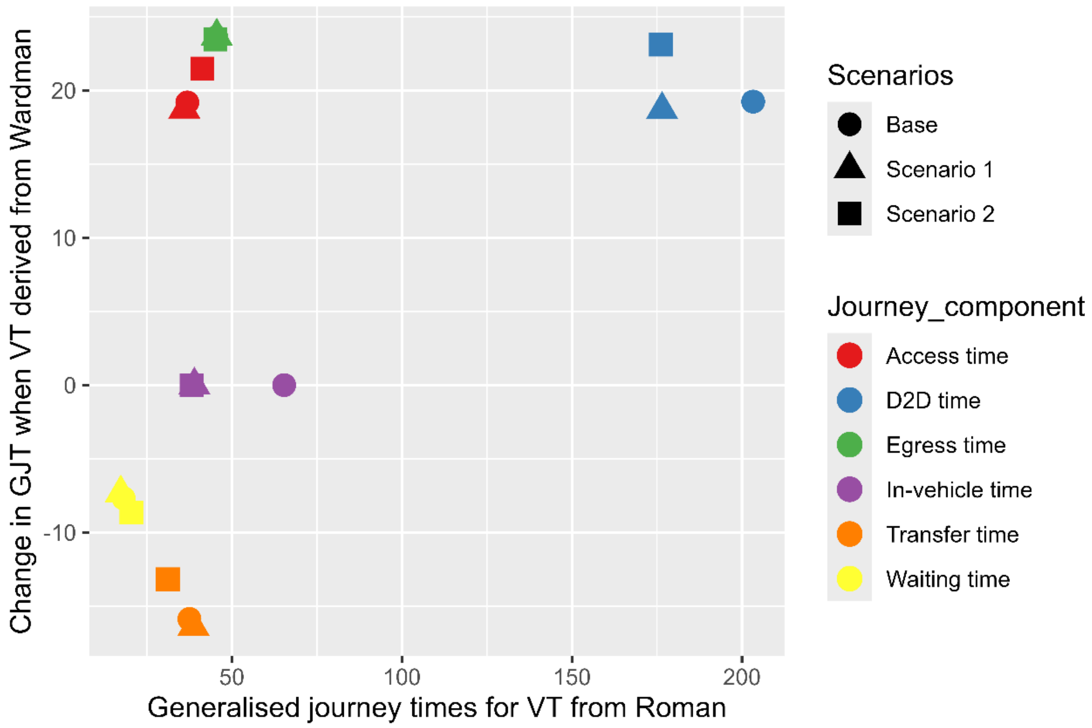


Figure 6.18 Comparison of generalised journey time components for different values of time

#### 6.5.4.2 Weighted Average Travel Time change

In the preceding section, the analysis focused on the door-to-door journey time to examine the spatial variations in accessibility across the city. It then evaluated the impact of understanding the generalised journey time on each journey stage. However, the spatial variation itself was not explicitly presented. In this section, a comparison is made between two indicators, highlighting their differences in terms of spatial variation. This comparison illustrates how different factors or measures contribute to variations in accessibility across different areas of the city.

Door-to-door journey time (D2D) is a simple accessibility indicator that averages the travel time from a specific location to all other possible locations. This measure assumes all destinations are equally important, regardless of their characteristics such as population, which may not always reflect real-world scenarios.

Weighted Average Travel Time (WATT) is a more sophisticated accessibility indicator that considers the attractiveness of the different destinations when calculating the average travel time. Chapter 3 section 3.5 shows the equation to calculate WATT. The attractiveness can be the gross domestic product (GDP), employment or population of the destination. In this study, population is used, meaning that more populous locations will have a higher impact on the overall average. For instance, if a location is far away but highly populated, it would affect the WATT more significantly than a close but less populated location. This can be more useful in real-world applications, where certain destinations (like major destinations) are more significant than others.

Additionally, when calculating the WATT, a generalised journey time is employed rather than a door-to-door journey time. This means that the calculation considers the disutility associated with different journey components and assigns weighting factors to components.

To determine the relationship between two indicators (D2D and WATT), the correlation coefficients were calculated for the corridor from West Midlands to London in the base case, scenario 1, and scenario 2. The correlation coefficients obtained were 0.95, 0.95, and 0.94, respectively. Moreover, the correlation values for the corridor from West Midlands to East Midlands in the base case, scenario 1, and scenario 2 are 0.98, 0.97, and 0.98, respectively. Although these correlation coefficients indicate a strong positive relationship between the indicators in all scenarios, it is essential to recognise that the magnitude of benefit differs significantly depending on the specific scenario. While the correlation values may appear similar, the actual impact or benefit derived from the indicators can vary significantly between indicators.

Figure 6.19 and Figure 6.20 show the percentage change of both D2D journey time and WATT accessibility indicators for Scenario 1 and Scenario 2 across different locations in the West Midlands to London corridors. The light-yellow zones on the map represent areas where there is no noticeable improvement in accessibility resulting from the construction of the High-Speed Rail system. These zones show that passengers within these areas may still prefer to use conventional trains rather than preferring for HSR trains. On the other hand, the darker zones on the map experience the most substantive benefits in terms of accessibility due to the implementation of the new HSR system. These areas benefit from improved connectivity and enhanced access to transportation options, indicating that passengers in these zones are likely to benefit the most from the introduction of the HSR infrastructure.

Table 6.10 shows the average percentage change in both D2D journey time and WATT indicators across the locations. The aim is not to compare the scenarios but to compare the differences due to the indicator used. Overall, it is obvious that percentage change representing the benefit obtained is less with WATT indicators.

Moreover, comparing Table 6.10 and Table 6.11 allows to observe the differences in accessibility caused by the different destinations. The accessibility of Coventry to East Midlands is more impacted by the HSR compared to its accessibility to London. In Table 6.11, the WATT to East Midlands for Coventry in Scenario 1 (8.32 percentage) is considerably higher than the WATT to London (0.45 percentage) in Table 6.10. Wolverhampton and Solihull show higher accessibility to the East Midlands compared to London. In Table 6.11, the WATT value change for Wolverhampton and Solihull to the East Midlands are lower than their respective values to London in Table 6.10 However, Birmingham, Dudley, Sandwell, and Walsall exhibit higher accessibility to London compared to the East Midlands. These differences demonstrate the varying impacts and dynamics of accessibility based on the chosen destination in the context of the study.

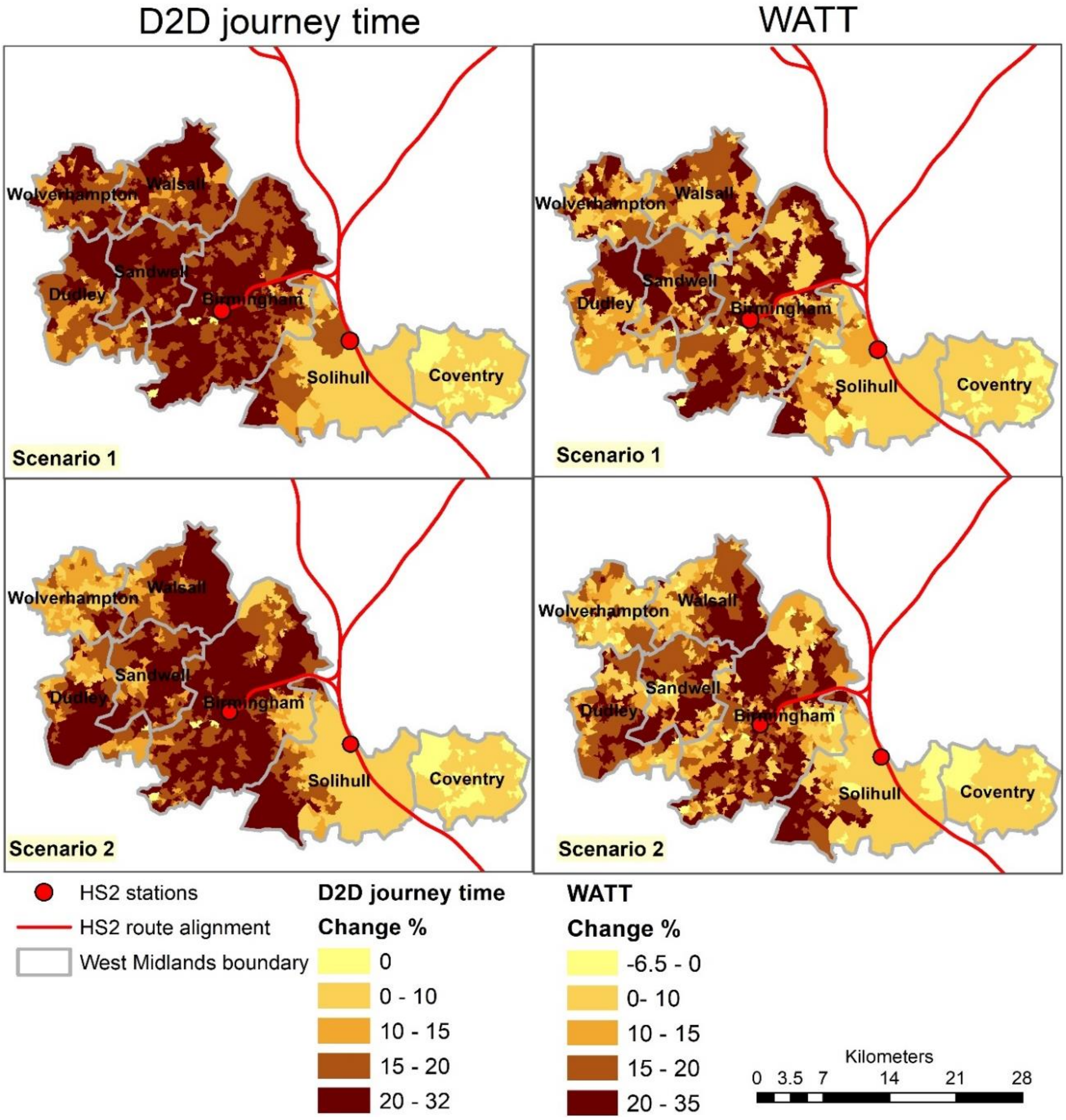


Figure 6.19 Spatial distribution of percentage change of D2D time and WATT to London

Table 6.10 Average percentage change of D2D time and WATT to London

| | D2D journey time | | WATT | |
|---|---|---|---|---|
| | **Scenario 1** | **Scenario 2** | **Scenario 1** | **Scenario 2** |
| **Birmingham** | 21.69 | 21.28 | 17.98 | 16.98 |
| **Coventry** | 0.76 | 0.59 | 0.45 | 0.72 |
| **Dudley** | 18.53 | 18.27 | 15.15 | 16.16 |
| **Sandwell** | 21.78 | 19.91 | 17.91 | 17.24 |
| **Solihull** | 12.51 | 15.30 | 9.97 | 12.72 |
| **Walsall** | 20.04 | 19.46 | 15.87 | 14.12 |
| **Wolverhampton** | 18.72 | 12.05 | 13.89 | 9.34 |

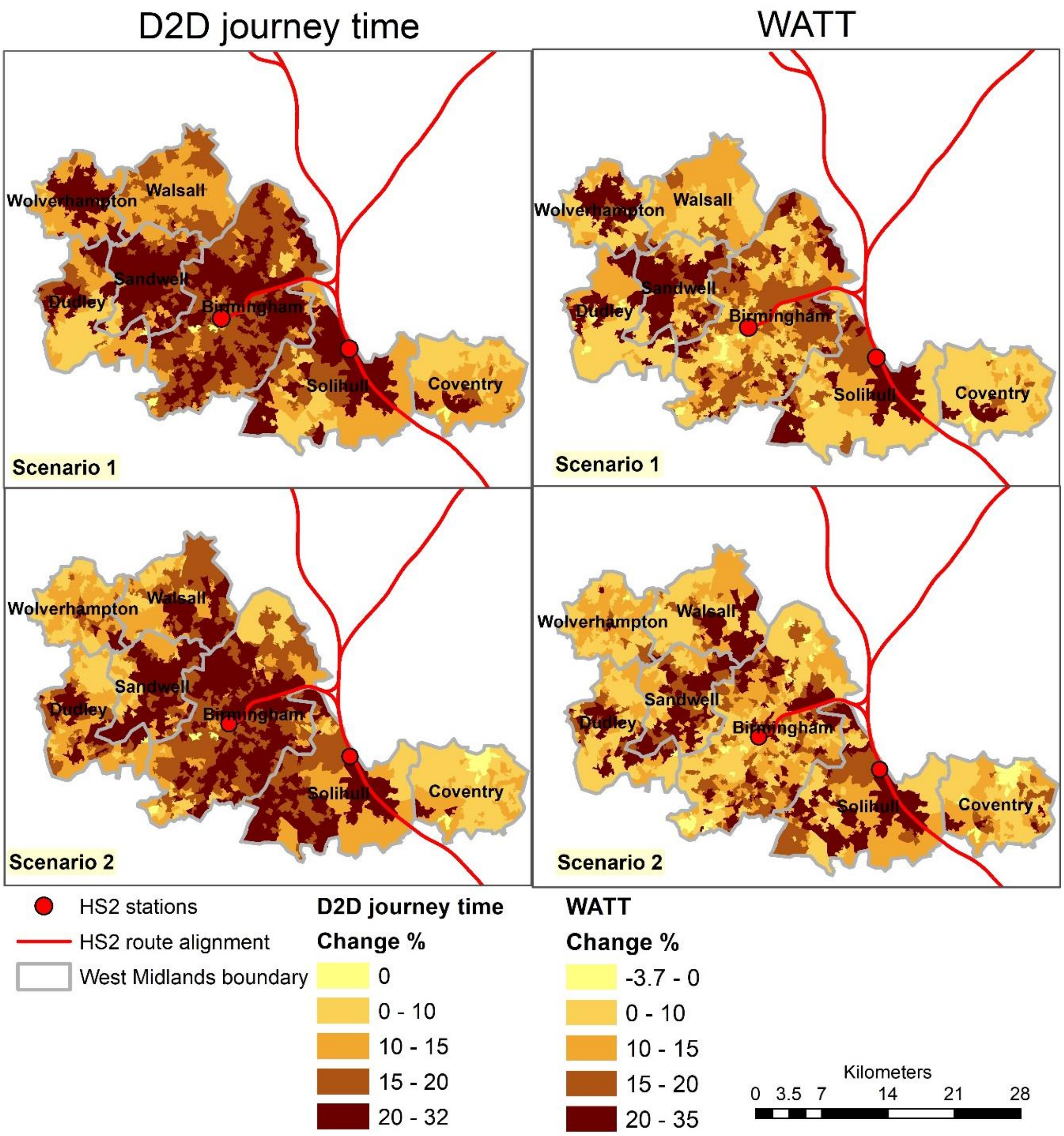


Figure 6.20 Spatial distribution of percentage change of D2D time and WATT to East Midlands

Table 6.11 Average percentage change of D2D time and WATT to East Midlands

| | D2D journey time | | WATT | |
|---|---|---|---|---|
| | **Scenario 1** | **Scenario 2** | **Scenario 1** | **Scenario 2** |
| **Birmingham** | 19.64 | 18.91 | 13.75 | 12.88 |
| **Coventry** | 11.75 | 8.23 | 8.32 | 9.16 |
| **Dudley** | 15.48 | 15.11 | 12.69 | 12.82 |
| **Sandwell** | 21.84 | 18.57 | 17.71 | 15.62 |
| **Solihull** | 16.05 | 19.71 | 12.01 | 15.55 |
| **Walsall** | 15.21 | 16.37 | 11.20 | 11.69 |
| **Wolverhampton** | 18.78 | 10.91 | 15.49 | 9.91 |

## 6.6 Conclusion

This chapter presents the practical implementation of the door-to-door approach to enhance the analysis of intercity travel accessibility. The door-to-door approach, combining both intra-city and inter-city segments, provides a comprehensive understanding of intercity travel and reveal the spatial variations of accessibility patterns across the city. The convenience and accessibility of the HSR system for passengers depend on the effective interconnection of the station with other transport modes.

Specifically, this chapter investigated the benefits of constructing a new station versus integrating the high-speed railway line with an existing station, and has revealed measurable differences between these design options. The study used on the HS2 routes and focused on the West Midlands County to observe the resulting changes. The proposed HSR stations, whether a new station or an existing station, exhibit spatial variation throughout the county. The integration of these stations with other transport modes contributes to this variation. The existing New Street station demonstrates broader accessibility across the county, while the Curzon Street station offers greater benefits to specific boroughs within the area.

Moreover, the application of the door-to-door journey time approach allows for a comparison between the proposed scenarios and the base case, enabling the identification of zones that may not derive any benefit from HSR construction. Despite the similarity in average journey time benefits between the two scenarios, the spatial representation provides valuable insights into which regions are either winners or losers in terms of accessibility improvements.

It is important to note certain limitations and consider the unique features of this case study that may limit the transferability of the findings. Firstly, the analysis conducted in this chapter is based on the specific context of the HS2 and focuses on the West Midlands County. The findings and conclusions drawn from this study may not directly apply to other regions or alternative plans of the high-speed railway.

Additionally, while the door-to-door approach and the implementation of generalised journey time contribute to a comprehensive understanding of intercity travel accessibility, it is important to note that the analysis did not consider the direct cost of travel. This omission represents a limitation in the study. The direct costs play a significant role in passengers' decision-making processes and can have a substantial impact on travel behaviour. Therefore, the exclusion of direct costs can impact the accessibility advantages of HSR scenarios. Although the analysis may indicate improved accessibility in terms of generalised travel time, the absence of cost considerations may overshadow these advantages. However, estimating the cost for each corridor presents challenges due to the current status of the HS2 project, which is still under construction and not yet operational. The cost of travel on the HS2 line, including fares and other associated expenses, is subject to various factors, such as infrastructure investments, operational costs, demand projections, and pricing strategies. As a result, it is difficult to provide accurate cost estimations for intercity travel along the HS2 line.

Despite these limitations, the main points derived from this analysis hold broader transferability. The importance of considering the door-to-door journey time approach, integrating both intra-city and inter-city segments, can be applicable to other transportation planning contexts. Understanding the spatial variations of accessibility patterns across a city provides valuable insights for policymakers, urban planners, and transport authorities, facilitating informed decision-making and infrastructure development. The findings also highlight the significance of effective interconnection between HSR stations and other transport modes. This emphasises the need for comprehensive and integrated transport planning strategies to ensure convenient and seamless travel experiences for passengers.

# Chapter 7 CONCLUSIONS

## 7.1 Concluding Summary

This research aims to bridge significant gaps in our understanding of the impact of High-Speed Rail systems on accessibility. Previous studies have often evaluated accessibility improvements by focusing mainly on station-to-station travel times. However, this approach tends to oversimplify the complex interactions between local and regional integration, leading to an underestimation of overall accessibility effects. Consequently, this thesis was conducted to explore the factors influencing inter-city accessibility in the context of high-speed rail systems, using a door-to-door journey time approach.

To achieve objective 1 which is to *examine the factors that inffluence the accessibility benefits provided by High-speed railways in interconnected cities.* A comprehensive literature review was conducted in Chapter 2. Factors that influence the accessibility benefits of HSR systems have been systematically categorised into seven distinct categories. These categories consider the entirety of the HSR rail system and its various components, ensuring a holistic consideration of the door-to-door journey experience. The factors that have been identified encompass the following areas: (1) design characteristics of HSR corridors, (2) integration between transport networks, (3) infrastructure, service, and traffic management aspects, (4) the planning, design, and location of rail stations, (5) pricing and ticketing mechanisms, (6) travel planning and user information systems, as well as (7) considerations regarding traveller comfort, safety, and convenience. Two factors are examined among the seven identified: the impact of station location and its seamless integration with public transportation networks. These factors are particularly crucial when assessing accessibility from a door-to-door journey time perspective.

To achieve objective 2 which is to *explore tools to compute door-to-door journey time calculations for public transport modes.* Firstly, a literature review was conducted to find out prominent tools frequently employed in literature, which are ArcGIS Network Analyst (Moyano et al., 2018), Open Trip Planner (OTP) (Smith, 2018), and Google Maps API (Salonen and Toivonen, 2013; Jäppinen, Toivonen and Salonen, 2013). Then, in Chapter 3, a thorough evaluation of these route modelling tools was undertaken to determine the one that aligns best with the project's objectives. Open Trip Planner was chosen due to its advantageous features aligned with the research project's objectives.

Google Maps API presents limitations in terms of API call volume and the inability to incorporate new public transport routes or make adjustments to existing/new stations and frequencies.

ArcGIS Network Analyst toolbox provides aggregated total travel times between origins and destinations, lacking the level of detail required to fulfil the objective of this project—examining the durations of individual door-to-door journey components for intercity rail travel. Given these considerations, OTP emerges as the most suitable tool for this project. It not only provides the essential disaggregated outcomes but also affords more control in generating an extensive array of routes according to the specific requirements of the thesis.

Objective 4 *is to examine the relative importance of different components contributing to journey times.* Accomplishing this requires *an exploration of varied methods to defining and segmenting door-to-door travel time,* as outlined in objective 3. Therefore, both these objectives were addressed in Chapter 4. For the achievement of objective 3, two methods were compared: Method 1 involves a segmented calculation of travel time for each part of the journey within the origin and destination cities. Method 2 calculates intercity and intra-city journey times simultaneously, thereby considering the integration level of journey stages and the impact of waiting and transfer time.

Chapter 4 compares the outcomes achieved through the two methods across two case study corridors, Barcelona-Madrid, and Hamburg-Berlin. Using multiple corridor helped to identify some limitations and see the extent to which it is transferable. Considering the strengths and weaknesses outlined in Section 4.5.3, this thesis has chosen to adopt Method 2. Through this comparative process, the significance of journey time components became evident. The out-of-vehicle time (including access, egress, transfer and waiting time) can constitute up to 50% of the total journey time in certain instances. This has the potential to significantly affect the overall accessibility of the high-speed rail system.

Objective 5 is *to empirically evaluate the implications of the station location for inter-city accessibility.* Chapter 5 undertook analysis and comparison of the accessibility benefits provided by different locations of the HSR station relative to the city. This issue has been given particular importance in the UK recently with the changing plans for HS2 Phase 2 routes and stations in the East Midlands serving Derby and Nottingham. This chapter therefore employed HS2 corridors to conduct a quantitative assessment of the different station options for HS2 in the East Midlands regions of England. The analysis compared two station options: firstly, a station located at the East Midlands Hub at Toton (located on the city periphery), and secondly the option of HSR services directly connecting to existing city centre stations in Derby and Nottingham. The study addresses a critical consideration in HSR planning by considering both direct city centre connections and more peripheral placements.

The finding shows that the choice of station location plays a crucial role in terms of the potential benefits in accessibility brought about by a new HSR system. In the case of the East Midlands to London corridor, the results demonstrate that the contribution of access time to the station constitutes 26 percent of the total accessibility of rail trips, on average, for peripheral stations. This value drops to 20 percent for central stations. These findings further emphasise the trade-offs involved in choosing between peripheral and city centre station locations. This case could potentially impact the user type of HSR, as stated by Diao, Zhu and Zhu, (2017) that newly constructed peripheral HSR stations are more like airports, serving infrequent business or tourism journeys.

Objective 6 is to *empirically assess the influence of station integration levels on the overall accessibility of high-speed rail systems.* An investigation was undertaken to assess the advantages of constructing a new station versus integrating the high-speed railway line with an existing station. This examination aims to unveil distinctions between these design alternatives, primarily attributed to variations in the connectivity levels of the stations. This study centres on the HS2 routes, with a specific focus on the West Midlands County. The examination of proposed HSR stations exhibit spatial variation throughout the county due to the integration of these stations with various transport modes. Despite the similarity in average journey time benefits between the two scenarios, the spatial representation offers valuable insights into the regions that experience varying degrees of accessibility improvements—identifying both winners and losers. In order to achieve a balanced distribution of accessibility benefits across regions, it is important to carefully plan the integration of the new system with other modes of public transportation.

In conclusion, the utilisation of the accessibility assessment along with a door-to-door journey time perspective emphasises the significance of comprehensive planning for investments in High-Speed Rail. Complementary factors, station location and its integration level with public transport system, have high potential to change the distribution of benefits across different areas, consequently leading to an increase or decrease in the overall accessibility of cities. This approach highlights the importance of a holistic strategy in optimising the outcomes of HSR projects.

## 7.2 Summary of contribution to knowledge

This study has made the following empirical or methodological contributions to knowledge in the field of high-speed rail accessibility and related fields:

- Given the limited literature addressing intercity accessibility studies based on door-to-door travel time, this thesis applies a door-to-door travel time approach that simultaneously integrates both the inter- and intra-city part of a trip. Therefore, it provides a more precise and comprehensive accessibility analysis of intercity travel through high-speed rail.

- Previous studies have predominantly focused on evaluating accessibility within historical or existing contexts, rather than quantifying the prospective implications of a future High-Speed Rail network on accessibility. This study uses HS2 corridor to estimate the accessibility benefit of HSR on cities.
- HSR station locations have been examined and categorised; however, their spatial impacts have not yet been empirically assessed. To address this gap, the research adopts a comprehensive door-to-door travel time approach and evaluates the overall impact of station location and station integration levels on city accessibility.

## 7.3 Research limitations

Some limitations of this research have been identified and are outlined as follows. Firstly, in the scope of this study, the consideration of egress and access times to and from the rail station highlights the importance of accurately defining the station's service area. In this regard, this thesis chose to delineate the study area primarily based on administrative boundaries. While this approach offers certain advantages, such as ease of setting boundaries, it also comes with potential limitations. Administrative boundaries might not fully cover the actual catchment area that influences station usage patterns. For instance, in Chapter 6, consider the case of Birmingham Interchange, which lies on the boundary of West Midlands. While it may be administratively located within West Midlands, its influence extends beyond this boundary. In the analysis, this station could have a significant impact on neighbouring areas such as Warwickshire. However, administrative boundaries might not fully capture this cross-border influence. This could result in an underestimation or overestimation of average access/egress times. Future research may consider improving the methodology for defining the station’s service area.

Another limitation to acknowledge is the assumption of no alteration to existing conventional rail service network. It is expected to observe potential reduction in conventional railway services following the implementation of High-Speed Rail systems. The assumption of unchanged conventional rail service levels suggests that the accessibility benefits identified in the analysis may be overestimated. For example, in Chapter 6, Coventry appears to have limited benefits from the HSR system because the region still maintains advantages from conventional train services. Any reduction in conventional train services could negatively impact accessibility in Coventry, particularly if it does not benefit from HSR enhancements. In essence, while the analysis focuses on the benefits of HSR, it's important to recognise that changes to the conventional rail network could significantly influence accessibility outcomes in areas like Coventry. Therefore, future analyses should consider the potential impacts of both HSR implementation and changes to conventional rail services to provide a more comprehensive understanding of accessibility dynamics.

This study does not consider the long-term effect that the introduction of a new peripheral HSR station may have. For example, it has the potential to stimulate development in the surrounding area. The land-use impacts resulting from transportation investments are difficult to estimate, especially when attempting to do so at a detailed spatial scale. Therefore, the current findings of the study are prone to underestimating the full scope of long-term accessibility benefits tied to the new station. It is important to highlight that the study's focus is directed towards discerning the short-term impact of the HSR project on accessibility levels, and thus, the spatial distribution of the population has been maintained as a constant within the analysis.

Using accessibility indicators typically provide a simplified measure of access to services. They may not capture the full range of factors that influence decision-making. Accessibility indicators usually focus on a specific aspect of accessibility, such as travel time or distance to key destinations. While these indicators can quantify the ease of reaching destinations, they may struggle to quantify the benefits associated with improved accessibility, such as economic development, social inclusion, or environmental sustainability.

## 7.4 Recommendations for further research

This thesis raises several aspects that could be further improved in future studies. Firstly, the evaluation of edge station design options was not included in this study's case analysis due to a lack of the necessary information required for empirical assessment. While it could be feasible to choose an edge location within a city and perform an analysis, the level of station connectivity significantly influences the outcomes of the analysis. Unfortunately, gathering reliable data about station feeders, which contribute substantially to the analysis, proves challenging without a comprehensive understanding of the region. Given the unpredictability of these variables, this study cannot provide a meaningful basis for comparison. However, collaborating with local authorities to obtain information about potential options and the specific requirements of the region would be helpful in developing a meaningful station feeder network.

Secondly, the enhancement of generalised cost calculations could encompass a more comprehensive approach by incorporating the direct cost of a trip, which depends on the public transport fares. In the present study, however, incorporating this aspect faced challenges due to the ongoing construction of the high-speed railway. As a result, estimating fares for the high-speed railway proved to be complex. Furthermore, the lack of fare information for local public transport, in the required format for integration into the analysis, imposed an additional constraint. Incorporating direct costs into the generalised cost calculation would enhance the precision of the accessibility assessment and its practical applicability.

Third, the interaction between transportation systems and land use patterns is a critical aspect of urban planning and development. High-speed rail systems have the potential to significantly alter land use patterns, urban development trajectories, and the spatial distribution of population. Investigating how the introduction of high-speed rail systems influences these dynamics can provide valuable insights into the broader impacts of such projects. Prior to assessing the accessibility impact of HSR, predicting changes in land use patterns can be achieved through the use of Land Use and Transportation Interaction (LUTI) models. These models integrate transportation infrastructure plans with land use policies to forecast future land use scenarios, consider factors such as population growth, employment distribution, housing demand, and travel behaviour. By employing LUTI models, this research can extend its scope to estimate the potential impacts of HSR systems shaping land development patterns and optimising accessibility within urban areas.

Fourth, in Chapter 6, the objective is to assess the integration levels of stations, with a focus on using New Street Station and Curzon Street Station as case studies to explore the impacts of this factor. However, given the close proximity of these stations, a direct comparison may not yield useful insights. Therefore, when considering station connectivity within networks, a comparison between Old Oak Common and Easton Station could offer valuable insights for evaluating the assessment criteria. This expanded comparison could provide a more comprehensive understanding of how different station locations and network connectivity influence integration levels and overall accessibility within the transportation system.

## 7.5 Policy and Practical implications

Shifting the accessibility assessment of HSR systems from a station-to-station journey time to a door-to-door journey time approach holds significant policy implications. These aspects highlight the importance of a holistic perspective in HSR planning and analysis.

First, when evaluating HSR accessibility, it is crucial not only to consider average access and egress times but also to account for the spatial variations in these times. These variations are crucial to understanding the complete door-to-door journey experience for HSR passengers. The analysis of High-Speed Rail should encompass intermodal approaches, rather than solely relying on the station-to-station perspective, to assess the real impacts of HSR on accessibility improvements. Furthermore, this type of analysis has the potential to assist urban and regional transport authorities in identifying deficiencies related to the integration of stations within metropolitan transport systems. It also enables the evaluation of the consequences of local accessibility enhancements, such as the introduction of new metro lines or the enhancement of scheduling coordination between suburban trains and HSR services.

The practical implications of this research are as follows: The analysis of station locations indicates that central stations, typically situated in densely populated urban areas, offer shorter intra-city travel times due to their proximity to transit connections. In contrast, peripheral stations, while providing access to outlying regions, result in longer overall journey times due to their distance from urban centres. Enhancing existing central stations rather than constructing new peripheral High-Speed Rail stations may be more advantageous in terms of both average travel times and expected construction costs.

When evaluating the level of station integration, despite similar average journey time benefits in both scenarios, spatial representation reveals which areas experience either improvements or drawbacks in terms of accessibility. This study underscores the spatial variability of accessibility benefits associated with HSR, emphasising the need for a more thorough evaluation. As such, policymakers and transportation planners should consider the spatial impact when assessing the advantages of new investments.

## 7.6 Concluding remarks

The study makes a significant contribution by emphasising the importance of considering door-to-door travel times and strategic station placement in assessing accessibility through High-Speed Rail. It demonstrates how the integration level of HSR stations with public transport can enhance accessibility for cities. This research provides valuable insights for transportation planning, underlining the travel times, station locations, station integration level, and urban accessibility. In a world focused on sustainable transportation, understanding accessibility nuances is vital, and thus the study's emphasis on door-to-door journey times is a crucial step towards creating a more accurate representation of real-world travel experiences. As cities grow, informed decisions on transportation are critical; this study offers guidance for adapting HSR systems to urban needs, promoting better connectivity and efficiency. In summary, the study's comprehensive approach and insights offer a novel perspective, empowering planners to build more accessible, connected, and vibrant cities.

# Appendix A

## GERMANY

**Operator**: Principal operator is Deutsche Bahn AG (DB) www.bahn.de
Many regional services are run by private operators – these are specified in the table heading (or by footnotes for individual trains).

**Services**: Trains convey first- and second-class seating accommodation unless otherwise shown (by '2' in the column heading, a footnote or a general note in the table heading). Overnight sleeping car (🛏) and couchette (▬) trains do not necessarily convey seating accommodation - refer to individual footnotes for details. Descriptions of sleeping and couchette cars appear on page 10.

There are various categories of trains in Germany. The type of train is indicated by the following letter codes above each column (or by a general note in the table heading):

| | | | | | |
|---|---|---|---|---|---|
| *ICE* | **InterCity Express** | German high-speed (230–320 km/h) train. | *IRE* | **InterRegio Express** | Regional express train. |
| *EC* | **EuroCity** | International express train. | *RE* | **Regional Express** | Regional semi-fast train. |
| *IC* | **InterCity** | Internal express train. | *RB* | **Regional Bahn** | Regional stopping train. |
| *ALX* | **alex** | Regional express train operated by *Vogtlandbahn*. | *S-Bahn* | | Suburban stopping train. |
| *FLX* | **Flixtrain** | Independent long-distance operator – see special table below. | | | |
| *RJX/RJ* | **Railjet** | Austrian express train. Conveys first and economy (2nd) class. *Business class* also available to first class ticket holders (supplement payable). | | | |
| *TGV* | **Train à Grande Vitesse** | French high-speed (320 km/h) train. Reservation compulsory for all international journeys. | | | |

Overnight services:

| | | |
|---|---|---|
| *NJ* | **ÖBB nightjet** | Quality overnight express train operated by Austrian Railways. All services convey *Deluxe* sleeping cars (1/2/3 berth) with en-suite shower and WC, standard sleeping cars (1/2/3 berth), couchettes (4/6 berth) and 2nd class seats (in a compartment). **Reservation compulsory.** For further details see pages 10 and 35. |
| *EN* | **EuroNight** | Other international overnight express train. See also pages 10 and 35. |
| *D* | **Durchgangszug** | Or **Schnellzug** – other express train (day or night); rarely used nowadays. |

**Timings**: Valid **June 11 - December 14**, 2019 (except where shown otherwise).

Many long distance trains operate on selected days only for part of the journey. These are often indicated in the train composition footnote by showing the dated journey segment within brackets. For example '🚆 Leipzig - Hannover ( - Dortmund ⑦)' means that the train runs daily (or as shown in the column heading) between Leipzig and Hannover, but only continues to Dortmund on Sundays. Additional footnotes/symbols are often used to show more complex running dates, e.g. '🚆 (München ⊡ - ) Nürnberg - Hamburg' means that the train runs only on dates in note ⊡ between München and Nürnberg, but runs daily (or as shown in the column heading) between Nürnberg and Hamburg. Please note that international overnight trains that are not intended for internal German journeys are not usually shown in the German section (refer to the International section).

**Engineering work** may occasionally disrupt services at short notice (especially at weekends and during holiday periods), so it is advisable to check timings locally before travelling. Please see panel below for information regarding major engineering work alterations affecting long-distance services during this timetable period.

**Tickets**: There are three standard levels of fares, corresponding to travel by (in ascending order of price): ○ Regional trains. ○ *IC/EC* trains. ○ High-speed *ICE* (also *TGV/RJ*) trains. A variable supplement is payable for sleeping car and couchette accommodation (and sometimes seating) on overnight *EN/NJ* trains, the cost of which depends on the type required. Please note that Interrail and Eurail pass holders may have to pay a special fare on overnight trains.

**Catering**: Two types of catering are indicated in the tables: 🍷 Bordbistro – hot and cold drinks, snacks and light meals (at-seat service on certain trains); ✕ Bordrestaurant – full restaurant car service (bordbistro also available). First class passengers on *ICE* and *IC* trains benefit from an at-seat service. On overnight trains 🍷 indicates that drinks and light snacks are available, usually from the sleeping or couchette car attendant (the refreshment service may only be available to sleeping and couchette car passengers).

**Reservations**: Reservation compulsory for travel in sleeping car and couchette accommodation on overnight *EN* trains (also in the seating accommodation of *ÖBB nightjet* services). Optional reservations are available on *ICE/EC/IC* trains (€ 4,50 in second class, € 5,90 in first class).

**Holidays**: Dec. 25, 26, Jan. 1, Apr. 19, 22, May 1, 30, June 10 and Oct. 3 are German national public holidays (trains marked ⚒ or Ⓐ do not run). In addition there are other regional holidays as follows: Jan. 6 – Heilige Drei Könige (Epiphany), June 20 – Fronleichnam (Corpus Christi), Aug. 15 – Mariä Himmelfahrt (Assumption), Oct. 31 – Reformationstag (Reformation Day), Nov. 1 – Allerheiligen (All Saints Day) and Nov. 20 – Buß und Bettag. On these days the regional service is usually that applicable on ⑦ (please refer to individual footnotes).

### HAMBURG - BERLIN - DRESDEN 840

| km | | *EC* 171 | *ICE* 701 | *ICE* 505 | *EC* 173 | *ICE* 903 | *ICE* 703 | *ICE* 507 | *EC* 379 | *ICE* 599 | *ICE* 705 | *EC* 175 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ①–⑤ | ①–⑥ | | ①–⑤ | ⑥⑦ | | | | | |
| | | P✕ | M✕ | M✕ | H✕ | ✕ | M✕ | M✕ | L✕ | F✕ | ✕ | P✕ |
| 0 | **Hamburg** Altona d. | ... | 0512 | 0618 | 0636 | 0721 | 0721 | 0819 | ... | 0921 | 1019 | ... |
| 7 | **Hamburg** Hbf 830 d. | ... | 0527 | 0635 | 0648 | 0738 | 0738 | 0835 | 0851 | 0936 | 1035 | ... |
| 54 | Büchen 830 d. | ... | \| | \| | 0714 | \| | \| | \| | 0914 | \| | \| | ... |
| 122 | Ludwigslust 837 d. | ... | 0613 | \| | 0741 | \| | \| | \| | 0941 | \| | \| | ... |
| 167 | Wittenberge 837 d. | ... | 0631 | \| | 0802 | \| | \| | \| | 1002 | \| | \| | ... |
| 280 | **Berlin** Spandau 837 d. | ... | 0712 | 0810 | 0846 | 0912 | 0912 | 1010 | 1046 | 1112 | 1210 | ... |
| 293 | **Berlin** Hbf 837 a. | ... | 0722 | 0820 | 0855 | 0922 | 0922 | 1020 | 1055 | 1122 | 1220 | ... |
| 293 | **Berlin** Hbf 835 d. | 0659 | 0737 | 0830 | 0859 | \| | 0937 | 1030 | 1059 | 1128 | \| | 1259 |
| 299 | **Berlin** Südkreuz 835 d. | 0705 | 0742 | 0837 | 0905 | 0930 | 0942 | 1037 | 1105 | 1135 | 1229 | 1305 |
| | *Leipzig Hbf* 850 a. | \| | ... | 0942 | \| | ... | ... | 1142 | \| | 1242 | ... | \| |
| 433 | Elsterwerda 843 835 d. | \| | ... | ... | \| | ... | ... | ... | \| | ... | ... | \| |
| 486 | **Dresden** Neustadt a. | 0900 | ... | ... | 1100 | ... | ... | ... | 1300 | ... | ... | 1500 |
| 490 | **Dresden** Hbf 843 a. | 0907 | ... | ... | 1107 | ... | ... | ... | 1307 | ... | ... | 1507 |

| km | | *ICE* 707 | *ICE* 1601 | *EC* 177 | *ICE* 709 | *ICE* 803 | *ICE* 603 | *EC* 179 | *ICE* 801 | *ICE* 1605 | *ICE* 1605 | *ICE* 1705 | *IC* 2071 | *IC* 2079 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ⑤f | | | | ⑥ | ⑧ | ⑧d | | |
| | | M✕ | M✕ | P✕ | M✕ | ✕ | M✕ | P✕ | B✕ | ✕ | M✕ | J✕ | ✕ | ✕ |
| 0 | **Hamburg** Altona d. | 1121 | 1218 | 1238 | 1321 | 1333 | 1419 | 1437 | 1518 | 1618 | 1618 | 1618 | 1638 | ... |
| 7 | **Hamburg** Hbf 830 d. | 1136 | 1235 | 1251 | 1338 | 1349 | 1435 | 1451 | 1537 | 1635 | 1635 | 1635 | 1651 | ... |
| 54 | Büchen 830 d. | \| | \| | 1314 | \| | \| | \| | 1514 | \| | \| | \| | \| | 1714 | ... |
| 122 | Ludwigslust 837 d. | \| | \| | 1341 | \| | \| | \| | 1541 | \| | \| | \| | \| | 1741 | ... |
| 167 | Wittenberge 837 d. | \| | \| | 1402 | \| | \| | \| | 1602 | \| | \| | \| | \| | 1802 | ... |
| 280 | **Berlin** Spandau 837 d. | 1312 | 1410 | 1446 | 1512 | 1527s | 1610 | 1646 | 1712 | 1810 | 1810 | 1810 | 1846 | ... |
| 293 | **Berlin** Hbf 837 a. | 1322 | 1420 | 1455 | 1522 | 1540 | 1620 | 1655 | 1722 | 1820 | 1820 | 1820 | 1855 | ... |
| 293 | **Berlin** Hbf 835 d. | 1337 | 1430 | 1459 | 1537 | \| | 1630 | 1659 | 1737 | \| | 1830 | 1830 | \| | 1859 |
| 299 | **Berlin** Südkreuz 835 d. | 1342 | 1437 | 1505 | 1542 | 1549 | 1637 | 1705 | 1742 | 1831 | 1837 | 1837 | 1903 | 1905 |
| | *Leipzig Hbf* 850 a. | ... | 1542 | \| | ... | ... | 1742 | \| | ... | ... | 1942 | 1942 | ... | \| |
| 433 | Elsterwerda 843 835 d. | ... | ... | \| | ... | ... | ... | 1826 | ... | ... | ... | ... | ... | 2026 |
| 486 | **Dresden** Neustadt a. | ... | ... | 1700 | ... | ... | ... | 1900 | ... | ... | ... | ... | ... | 2100 |
| 490 | **Dresden** Hbf 843 a. | ... | ... | 1707 | ... | ... | ... | 1907 | ... | ... | ... | ... | ... | 2107 |

| | *ICE* 697 | *ICE* 1607 | *IC* 2073 | *IC* 2073 | *IC* 1912 | *ICE* 993 | *ICE* 907 | *ICE* 905 | *ICE* 909 | *ICE* 809 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ⑧ | | ⊡ | ②y | | ⑧ | | ⑤f | ⑦ | |
| | ✕ | D✕ | U🍷 | U🍷 | 🍷 | G✕ | ✕ | ✕ | ✕ | | |
| **Hamburg** Altona d. | 1720 | 1819 | ... | ... | ... | 1921 | 2017 | 2136 | 2237 | 2237 | ... |
| **Hamburg** Hbf 830 d. | 1735 | 1835 | 1851 | 1851 | ... | 1936 | 2034 | 2151 | 2251 | 2251 | ... |
| Büchen 830 d. | \| | \| | 1914 | 1914 | ... | \| | \| | 2215 | 2315 | 2315 | ... |
| Ludwigslust 837 d. | 1819 | \| | 1941 | 1941 | ... | \| | 2119 | 2242 | 2342 | 2342 | ... |
| Wittenberge 837 d. | \| | \| | 2002 | 2002 | ... | \| | \| | 2303 | 0002 | 0002 | ... |
| **Berlin** Spandau 837 d. | 1910s | 2010 | 2046 | 2046 | 2040 | 2112 | 2211s | 2343s | 0042s | 0042s | ... |
| **Berlin** Hbf 837 a. | 1922 | 2020 | 2055 | 2055 | 2051 | 2122 | 2223 | 2355 | 0053 | 0053 | ... |
| **Berlin** Hbf 835 d. | \| | 2030 | ... | 2058 | 2059 | 2128 | \| | \| | \| | \| | ... |
| **Berlin** Südkreuz 835 d. | 1930 | 2037 | ... | 2105 | 2105 | 2135 | 2231 | 0003 | 0101 | 0101 | ... |
| *Leipzig Hbf* 850 a. | ... | 2142 | ... | \| | \| | 2247k | ... | ... | ... | ... | ... |
| Elsterwerda 843 835 d. | ... | ... | ... | \| | \| | ... | ... | ... | ... | ... | ... |
| **Dresden** Neustadt a. | ... | ... | ... | 2300 | 2259 | ... | ... | ... | ... | ... | ... |
| **Dresden** Hbf 843 a. | ... | ... | ... | 2307 | 2306 | ... | ... | ... | ... | ... | ... |

| | *IC* 1978 | *ICE* 908 | *ICE* 808 | *IC* 2070 | *ICE* 1606 | *IC* 2078 | *ICE* 806 | *IC* 2076 | *IC* 2072 |
|---|---|---|---|---|---|---|---|---|---|
| | ①g | Ⓐ | ①–⑥ | | ①–⑥ | ①–⑥ | | ③⑦ | ⊖ |
| | 🍷 | ✕ | ✕ | ✕ | ✕ | ✕ | E✕ | z🍷 | U🍷 |
| **Dresden** Hbf 843 d. | ... | ... | ... | ... | ... | 0544 | ... | 0644 | 0644 |
| **Dresden** Neustadt d. | ... | ... | ... | ... | ... | 0551 | ... | 0651 | 0651 |
| Elsterwerda 843 835 d. | ... | ... | ... | ... | ... | 0626 | ... | 0726 | 0726 |
| *Leipzig Hbf* 850 d. | ... | ... | ... | ... | 0616 | \| | 0716 | \| | \| |
| **Berlin** Südkreuz 835 d. | 0458 | 0519 | 0629 | 0658 | 0724 | 0735s | 0827 | 0834s | 0836 |
| **Berlin** Hbf 835 a. | \| | \| | \| | \| | 0729 | 0741 | 0832 | 0841 | 0844 |
| **Berlin** Hbf 837 d. | 0506 | 0528 | 0638 | 0706 | 0740 | ... | 0838 | ... | 0906 |
| **Berlin** Spandau 837 d. | 0517 | 0538 | 0648 | 0717 | 0750 | ... | 0848 | ... | 0917 |
| Wittenberge 837 d. | 0601 | 0621 | \| | 0802 | \| | ... | \| | ... | 1002 |
| Ludwigslust 837 d. | 0620 | 0641 | 0742 | 0820 | \| | ... | \| | ... | 1020 |
| Büchen 830 d. | 0648 | \| | \| | 0848 | \| | ... | \| | ... | 1048 |
| **Hamburg** Hbf 830 a. | 0712 | 0725 | 0824 | 0911 | 0924 | ... | 1021 | ... | 1112 |
| **Hamburg** Altona a. | 0724 | 0742 | 0839 | 0923 | 0939 | ... | 1038 | ... | ... |

| | *IC* 2072 | *ICE* 1604 | *ICE* 1704 | *ICE* 1604 | *ICE* 696 | *EC* 178 | *IC* 2322 | *ICE* 602 | *ICE* 802 | *EC* 176 | *ICE* 1600 | *ICE* 800 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ⑧ | ①–⑤ | ⑥ | | | ⑥ | | | | | |
| | U 🍷 | N✕ | hJ ✕ | ✕ | A✕ | P✕ | O | M✕ | M✕ | P✕ | M✕ | M✕ |
| **Dresden** Hbf 843 d. | | ... | | ... | ... | 0846 | 0922 | ... | ... | 1046 | ... | ... |
| **Dresden** Neustadt d. | ... | ... | ... | ... | ... | 0852 | \| | ... | ... | 1052 | ... | ... |
| Elsterwerda 843 835 d. | ... | ... | ... | ... | ... | \| | 0959 | ... | ... | \| | ... | ... |
| *Leipzig Hbf* 850 d. | ... | 0818 | 0818 | ... | 0916 | \| | \| | 1016 | ... | \| | 1216 | ... |
| **Berlin** Südkreuz 835 d. | 0836 | 0925 | 0925 | 0931 | 1024 | 1034s | 1120 | 1124 | 1219 | 1236 | 1324 | 1419 |
| **Berlin** Hbf 835 a. | 0844 | 0930 | 0930 | \| | 1029 | 1041 | 1125 | 1129 | 1224 | 1241 | 1329 | 1424 |
| **Berlin** Hbf 837 d. | 0906 | 0940 | 0940 | 0940 | 1038 | ... | ... | 1140 | 1238 | 1306 | 1340 | 1438 |
| **Berlin** Spandau 837 d. | 0917 | 0950 | 0950 | 0950 | 1048 | ... | ... | 1150 | 1248 | 1317 | 1350 | 1448 |
| Wittenberge 837 d. | 1002 | \| | \| | \| | \| | ... | ... | \| | \| | 1402 | \| | \| |
| Ludwigslust 837 d. | 1020 | \| | \| | \| | \| | ... | ... | \| | \| | 1420 | \| | \| |
| Büchen 830 d. | 1048 | \| | \| | \| | \| | ... | ... | \| | \| | 1448 | \| | \| |
| **Hamburg** Hbf 830 a. | 1112 | 1124 | 1124 | 1124 | 1221 | ... | ... | 1324 | 1421 | 1511 | 1525 | 1621 |
| **Hamburg** Altona a. | ... | 1139 | 1139 | 1139 | 1238 | ... | ... | 1339 | 1438 | 1527 | 1539 | 1638 |

| | *EC* 174 | *ICE* 508 | *ICE* 690 | *EC* 378 | *ICE* 506 | *ICE* 706 | *EC* 172 | *ICE* 504 | *ICE* 704 | *EC* 170 | *ICE* 502 | *ICE* 702 | *ICE* 898 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ⑥v | | ♠ | ⑤⑦r | ♣ |
| | P✕ | M✕ | F✕ | L✕ | M✕ | M✕ | H✕ | M✕ | M✕ | P✕ | M✕ | M✕ | ✕ |
| **Dresden** Hbf 843 d. | 1246 | ... | ... | 1446 | ... | ... | 1646 | ... | ... | 1846 | ... | ... | ... |
| **Dresden** Neustadt d. | 1252 | ... | ... | 1452 | ... | ... | 1652 | ... | ... | 1852 | ... | ... | ... |
| Elsterwerda 843 835 d. | \| | ... | ... | \| | ... | ... | \| | ... | ... | \| | ... | ... | ... |
| *Leipzig Hbf* 850 d. | \| | 1416 | 1516 | \| | 1616 | ... | \| | 1816 | ... | \| | 2016 | ... | ... |
| **Berlin** Südkreuz 835 d. | 1438 | 1524 | 1624 | 1636 | 1724 | 1820 | 1836 | 1924 | 2019 | 2034s | 2124 | 2219 | 2228 |
| **Berlin** Hbf 835 a. | 1443 | 1529 | 1629 | 1641 | 1729 | 1826 | 1841 | 1929 | 2026 | 2041 | 2129 | 2224 | \| |
| **Berlin** Hbf 837 d. | 1506 | 1540 | 1638 | 1706 | 1740 | 1838 | 1906 | 1940 | 2038 | ... | 2138 | 2238 | 2238 |
| **Berlin** Spandau 837 d. | 1517 | 1550 | 1648 | 1717 | 1750 | 1848 | 1917 | 1950 | 2048 | ... | 2148 | 2248 | 2248 |
| Wittenberge 837 d. | 1602 | \| | \| | 1802 | \| | \| | 2002 | \| | \| | ... | 2229 | 2330 | 2330 |
| Ludwigslust 837 d. | 1621 | \| | \| | 1820 | \| | \| | 2020 | \| | \| | ... | 2249 | 2348 | 2348 |
| Büchen 830 d. | 1648 | \| | \| | 1848 | \| | \| | 2048 | \| | \| | ... | \| | \| | \| |
| **Hamburg** Hbf 830 a. | 1711 | 1724 | 1822 | 1911 | 1924 | 2023 | 2115 | 2124 | 2221 | ... | 2333 | 0033 | 0033 |
| **Hamburg** Altona a. | 1724 | 1741 | 1838 | ... | 1938 | 2038 | 2136 | 2140 | 2238 | ... | 2350b | ... | 0048 |

## 650 MADRID - ZARAGOZA - BARCELONA — High-speed services

| km | | Av 10263 ②–⑤ | AVE 3263 ① | AVE 3053 ①④⑤ | AVE 3061 ①–④ | Av 8087 | AVE 3463 ⑥⑦ | AVE 3063 ①–⑤ | AVE 3071 ①–⑤ | AVE 3271 ①–④ | AVE 10483 ⑥⑦ | AVE 3073 ①–⑤ | AVE 3073 ⑥⑦ | AVE 3081 ①–⑤ | AVE 3283 ①–④ | AVE 3083 | AVE 3093 | AVE 3103 | AVE 3993 | AVE 3943 | AVE 3113 ①–⑤ | AVE 3113 ⑥⑦ | AVE 3123 Ⓑ | AVE 3123 ⑥ | AVE 9724 19725 M | AVE 3141 Ⓑ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Sevilla* **660** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0850 | ... | ... | ... | ... | ... | ... |
| | *Málaga* **660** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0835 | \| | ... | ... | ... | ... | ... | ... |
| 0 | **Madrid** Puerta de Atocha d. | ... | ... | 0550 | 0610 | ... | 0620 | 0630 | 0700 | 0720 | ... | 0730 | 0730 | 0800 | 0820 | 0830 | 0930 | 1030 | \| | \| | 1130 | 1130 | 1230 | 1230 | 1325 | 1400 |
| 64 | Guadalajara-Yebes d. | ... | ... | \| | \| | ... | \| | \| | \| | \| | ... | 0754 | 0754 | \| | \| | \| | \| | \| | \| | \| | \| | \| | \| | \| | 1350 | \| |
| 221 | Calatayud d. | ... | ... | \| | \| | ... | 0716 | 0726 | \| | \| | ... | \| | \| | \| | \| | \| | \| | \| | \| | \| | 1226 | 1226 | \| | \| | \| | \| |
| 307 | **Zaragoza** Delicias d. | 0615 | 0620 | 0706 | \| | ... | 0742 | 0752 | \| | \| | 0800 | 0852 | 0852 | \| | 0936 | 0946 | 1046 | 1146 | 1236 | 1236 | 1252 | 1252 | 1346 | 1346 | 1452 | \| |
| 447 | Lleida d. | 0704 | 0705 | 0750 | \| | 0800 | 0826 | \| | \| | \| | 0855 | 0937 | 0937 | \| | \| | \| | 1131 | \| | 1322 | 1322 | 1337 | 1337 | 1431 | 1431 | \| | \| |
| 526 | Camp de Tarragona d. | 0736 | 0735 | 0819 | \| | 0832 | 0854 | \| | \| | \| | 0929 | 1005 | 1005 | \| | \| | \| | 1159 | \| | 1351 | 1351 | 1405 | 1405 | \| | \| | 1547 | \| |
| 621 | **Barcelona** Sants a. | 0815 | 0810 | 0855 | 0840 | 0908 | 0929 | 0920 | 0930 | 0950 | 1005 | 1040 | 1040 | 1030 | 1105 | 1115 | 1234 | 1315 | 1425 | 1425 | 1440 | 1440 | 1530 | 1530 | 1624 | 1630 |
| | *Girona* **657** a. | ... | ... | ... | ... | ... | 1023 | ... | 1023 | ... | ... | ... | 1128 | ... | ... | ... | 1322 | ... | ... | ... | 1529 | ... | 1618 | ... | 1723 | ... |
| | *Figueres Vilafant* **657** a. | ... | ... | ... | ... | ... | 1040 | ... | 1040 | ... | ... | ... | 1145 | ... | ... | ... | 1339 | ... | ... | ... | 1545 | ... | 1635 | ... | 1740 | ... |

| | Av 8167 Ⓑ | AVE 3143 Ⓑ | AVE 3151 ①–⑤ | AVE 3153 | AVE 3161 Ⓑ | Av 8187 | AVE 3163 ①–⑤ | AVE 3163 ⑥⑦ | AVE 3553 ⑤ | Av 10553 ④⑦ | AVE 3171 Ⓑ | Av 3793 ⑤⑦ | AVE 3991 | AVE 3941 | AVE 3173 | AVE 3181 Ⓑ | AVE 3183 ⑥ | AVE 3183 Ⓑ | AVE 3191 Ⓑ | Av 8207 | AVE 3931 G | AVE 3193 | AVE 3201 Ⓑ | AVE 3203 | AVE 3211 Ⓑ | Av 10593 Ⓑ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Sevilla* **660** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1450 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| *Málaga* **660** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1435 | \| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| **Madrid** Puerta de Atocha d. | ... | 1430 | 1500 | 1530 | 1600 | ... | 1630 | 1630 | 1635 | 1635 | 1700 | ... | \| | \| | 1730 | 1800 | 1830 | 1830 | 1900 | ... | ... | 1930 | 2000 | 2030 | 2125 | 2130 |
| Guadalajara-Yebes d. | ... | \| | \| | \| | \| | ... | \| | \| | \| | \| | \| | ... | \| | \| | 1754 | \| | \| | \| | \| | ... | ... | \| | \| | 2054 | \| | 2157 |
| Calatayud d. | ... | 1526 | \| | 1626 | \| | ... | \| | \| | \| | \| | \| | ... | \| | \| | \| | \| | \| | \| | \| | ... | ... | \| | \| | \| | \| | 2244 |
| **Zaragoza** Delicias d. | ... | 1552 | \| | 1652 | \| | ... | 1746 | 1746 | 1756 | 1805 | \| | 1805 | 1831 | 1831 | 1852 | \| | 1946 | 1946 | \| | ... | 2006 | 2046 | \| | 2152 | \| | 2310 |
| Lleida d. | 1600 | \| | \| | 1737 | \| | 1800 | \| | \| | ... | ... | \| | 1848 | 1918 | 1918 | 1937 | \| | \| | \| | \| | 2040 | 2053 | 2131 | \| | 2237 | \| | ... |
| Camp de Tarragona d. | 1632 | \| | \| | 1805 | \| | 1832 | 1844 | 1844 | ... | ... | \| | 1916 | 1947 | 1947 | 2005 | \| | 2045 | 2045 | \| | 2112 | 2125 | 2206 | \| | 2305 | \| | ... |
| **Barcelona** Sants a. | 1708 | 1721 | 1730 | 1840 | 1830 | 1908 | 1920 | 1920 | ... | ... | 1930 | 1951 | 2022 | 2022 | 2040 | 2030 | 2120 | 2120 | 2130 | 2148 | 2200 | 2240 | 2230 | 2340 | 2355 | ... |
| *Girona* **657** a. | ... | 1815 | ... | 1928 | ... | ... | 2008 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 2208 | ... | 2218 | ... | ... | ... | ... | ... | ... | ... |
| *Figueres Vilafant* **657** a. | ... | 1832 | ... | 1945 | ... | ... | 2025 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 2225 | ... | 2235 | ... | ... | ... | ... | ... | ... | ... |

| | AVE 3252 ①–④ | AVE 3772 ①–⑥ | AVE 3062 ①–⑥ | AVE 3260 ①–⑤ | AVE 3462 ①–④ | AVE 3930 G | AVE 3270 ①–④ | AVE 3072 | AVE 3070 ①–④ | AVE 3662 ①–⑤ | AVE 3082 ①–⑤ | AVE 3082 ⑥⑦ | AVE 3080 ①–⑥ | AVE 3940 | AVE 3990 | AVE 3092 ①–⑥ | AVE 3092 ⑦ | Av 8096 | AVE 3102 | AVE 3112 | AVE 3122 | AVE 9731 19730 M | AVE 3132 ①–⑥ | AVE 3142 | AVE 3152 | Av 3562 ⑤⑦ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Figueres Vilafant* **657** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0630 | 0655 | ... | ... | ... | ... | 0755 | ... | ... | 0855 | ... | ... | 1143 | ... | ... | ... | ... |
| *Girona* **657** d. | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0646 | 0711 | ... | ... | ... | ... | 0811 | ... | ... | 0911 | ... | ... | 1200 | ... | ... | ... | ... |
| **Barcelona** Sants d. | 0550 | ... | 0605 | 0625 | 0640 | 0650 | 0700 | 0705 | 0725 | 0740 | 0800 | 0800 | 0825 | 0830 | 0830 | 0900 | 0900 | 0920 | 1000 | 1100 | 1200 | 1250 | 1325 | 1400 | 1500 | 1515 |
| Camp de Tarragona d. | \| | ... | 0638 | \| | \| | 0725 | \| | \| | 0757 | \| | 0833 | 0833 | \| | 0905 | 0905 | \| | \| | 0957 | 1033 | \| | 1233 | 1322 | \| | 1433 | \| | 1548 |
| Lleida d. | \| | ... | 0704 | \| | \| | 0804 | \| | \| | \| | \| | 0859 | 0859 | \| | 0934 | 0934 | \| | \| | 1028 | 1059 | \| | 1259 | \| | \| | 1459 | \| | 1614 |
| **Zaragoza** Delicias d. | \| | 0705 | 0748 | \| | 0806 | 0845 | \| | 0831 | \| | \| | 0943 | 0943 | \| | 1020 | 1020 | 1026 | 1026 | ... | 1143 | 1226 | 1343 | 1425 | 1451 | 1543 | 1626 | 1655 |
| Calatayud d. | \| | 0736 | \| | \| | \| | ... | \| | \| | \| | \| | 1008 | 1008 | \| | \| | \| | \| | \| | ... | \| | \| | \| | \| | \| | 1608 | \| | ... |
| Guadalajara-Yebes d. | \| | 0822 | 0845 | \| | \| | ... | \| | \| | \| | \| | \| | \| | \| | \| | \| | \| | \| | ... | 1243 | \| | 1443 | \| | \| | \| | \| | ... |
| **Madrid** Puerta de Atocha a. | 0820 | 0850 | 0915 | 0855 | 0925 | ... | 0930 | 0950 | 1001 | 1010 | 1110 | 1110 | 1055 | \| | \| | 1145 | 1145 | ... | 1310 | 1345 | 1510 | 1545 | 1610 | 1710 | 1745 | ... |
| *Málaga* **660** a. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | \| | 1430 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| *Sevilla* **660** a. | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1402 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

| | AVE 3150 ①–⑤ | AVE 3942 | AVE 3992 | AVE 3162 ①–⑥ | AVE 3162 ⑦ | Av 8166 Ⓑ | AVE 3160 Ⓑ | AVE 3172 ①–⑥ | AVE 3172 ⑦ | AVE 3170 Ⓑ | AVE 3782 ⑤ | Av 10782 ④⑦ | AVE 3182 | Av 8186 | AVE 3180 ①–⑤ | AVE 3180 ⑦ | AVE 3192 | AVE 3190 Ⓑ | AVE 3202 | Av 8206 | AVE 3212 ⑤⑦ | AVE 3412 P | AVE 3610 ⑤⑦ | AVE 3222 ⑦ | Av 10222 ①–⑥ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Figueres Vilafant* **657** d. | ... | ... | ... | 1455 | ... | ... | ... | ... | 1545 | ... | | | 1655 | ... | ... | 1720 | 1755 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| *Girona* **657** d. | ... | ... | ... | 1511 | ... | ... | ... | ... | 1601 | ... | ... | ... | 1711 | ... | ... | 1736 | 1811 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| **Barcelona** Sants d. | 1525 | 1550 | 1550 | 1600 | 1600 | 1605 | 1625 | 1700 | 1700 | 1725 | ... | ... | 1800 | 1805 | 1825 | 1825 | 1900 | 1925 | 2000 | 2010 | 2100 | 2115 | 2125 | 2150 | 2200 | ... |
| Camp de Tarragona d. | \| | 1623 | 1623 | 1633 | 1633 | 1642 | \| | \| | \| | \| | ... | ... | 1833 | 1842 | \| | \| | 1932 | \| | 2033 | 2047 | 2133 | \| | \| | 2223 | 2237 | ... |
| Lleida d. | \| | 1649 | 1649 | 1659 | 1659 | 1713 | \| | \| | \| | \| | ... | ... | 1859 | 1913 | \| | \| | 1958 | \| | 2059 | 2118 | 2159 | \| | \| | 2250 | 2307 | ... |
| **Zaragoza** Delicias d. | \| | 1733 | 1733 | 1743 | 1743 | ... | \| | 1826 | 1826 | \| | 1900 | 1900 | 1943 | ... | \| | \| | 2041 | \| | 2143 | ... | 2243 | 2243 | \| | 2335 | 2354 | ... |
| Calatayud d. | \| | \| | \| | 1808 | 1808 | ... | \| | \| | \| | \| | \| | \| | 2008 | ... | \| | \| | \| | \| | \| | ... | \| | \| | \| | ... | ... | ... |
| Guadalajara-Yebes d. | \| | \| | \| | \| | \| | ... | \| | \| | \| | \| | \| | \| | \| | ... | \| | \| | \| | \| | 2243 | ... | \| | \| | \| | ... | ... | ... |
| **Madrid** Puerta de Atocha a. | 1755 | \| | \| | 1910 | 1910 | ... | 1855 | 1945 | 1945 | 1955 | 2020 | 2030 | 2110 | ... | 2055 | 2055 | 2200 | 2155 | 2310 | ... | 0002 | 0002 | 2355 | ... | ... | ... |
| *Málaga* **660** a. | ... | \| | 2146 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| *Sevilla* **660** a. | ... | 2120 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | .... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

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