EXPLORING THE RELATIONSHIP BETWEEN

URBAN FORM AND DOOR-TO-DOOR TRAVEL

TIME: A FOCUS ON HIGH-SPEED RAIL IN THE

UNITED STATES

By

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Abstract: High-speed rail (HSR) is gaining increasing attention in the United States due to its rapid development and success in Europe and Asia in recent decades. Traveling at a high speed, HSR is expected to increase the accessibilities of the cities it connects and is considered a competitive alternative to existing travel modes for short to medium distance intercity travel. While current HSR accessibility studies tend to focus primarily on the intercity portion of HSR travel, an HSR intercity trip is composed of both access/egress time to the traveling facilities at the intracity level and on-board travel time at the intercity level. To provide a more accurate measurement of total journey time, this research proposes and defines a door-to-door travel time framework that integrates trip segments at both the inter- and intra-city levels simultaneously. Based on this framework, three independent yet connected research components are conducted to better identify the accessibility benefits of HSR under the sprawling urban form of U.S. cities. First, this research explores how the compactness of cities can affect overall access time to traveling facility of intercity trips via different travel modes. Second, by accounting for access/egress time differences at different locations within a city, the door-to-door framework is introduced to examining the variations of the accessibility advantage of HSR over its competitors (i.e., air and auto) at the sub-city level. A case study on the proposed Dallas-Houston HSR corridor is carried out to demonstrate the feasibility of the approach and reveal where HSR holds accessibility advantage over existing intercity travel modes between the two cities. Last, a trend analysis on the urban form development of Dallas and Houston is carried out to explore the evolving urban form of the two cities from 2002 to 2014. Emphases are given on their implications on the proposed HSR project in the region. Results of this research can help policy makers and transportation planners more accurately evaluate the accessibility advantages of HSR and understand how HSR will compete with existing intercity travel modes at a finer spatial scale in the U.S. context.

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CHAPTER I

INTRODUCTION

High-speed rail and its impact on accessibility

High-speed rail (HSR) has experienced rapid development in numerous countries throughout the world in recent decades. Providing intercity passenger travel services with maximum speed at 200-250 kilometers per hour, HSR can be a competitive alternative to air and road transport for medium-distance (200-800 km) travel (Goetz 2012). In 1964, the first HSR line, Shinkansen, went into service between Tokyo and Osaka in Japan. The first Europe HSR line, known as the Train à Grande Vitesse (TGV) line, was opened to public in 1981 in France, connecting Paris and Lyon. In the 2000s, a huge wave of development in HSR occurred in more countries around the world, including Spain, China, Italy, South Korea, etc. (Albalate and Bel 2012). By 2016, over 30,000 km of HSR lines had been built worldwide (Wei et al. 2017).

The United States, albeit falling behind in HSR development, is showing increasing interests in adopting HSR as a new intercity travel mode. There have been initiatives trying to promote HSR in the United States since the early 1980s (Thompson 1994). Rail transport, especially HSR, showed signs of resurgence when the Obama administration passed the American Reinvestment and Recovery Act of 2009 (ARRA) that allocated $8 billion to identify and jump-start potential HSR development in the country (The White House 2009). The start of the construction of a state-wide HSR system in California marked a new milestone of HSR development in the United States. The Trump administration also showed intention to increase infrastructure spending and expressed interests in HSR (Formby 2017). With the increasing

interests in HSR in the United States, there also comes the need of evaluating the potential benefits of a HSR system to justify its adoption and establishment.

A new HSR system is expected to increase the accessibility of connected cities by reducing travel time. This increased accessibility brought by a HSR system is often linked to potential opportunities for economic development (Vickerman 1997; Levinson 2012; Martínez and Givoni 2012) and is often considered as one of the most important effects of HSR. For example, Yin, Bertolini and Duan (2015) argue reduced travel time brought by HSR plays a central role in HSR establishment and helps it win political and public support. Studies on accessibility, which serves as a good proxy for evaluating the economic potential of new transport infrastructure, are thus popular in HSR studies and can help urban and transportation planners assess the performance and benefits of a HSR system.

While accessibility studies of HSR have received increased attention, challenges exist when using traditional accessibility measures to modal competition between HSR and other major intercity travel modes, such as air and auto travel. More specifically, current studies on HSR accessibility tend to represent HSR network and connected cities in an arc-node system, in which cities are represented as single nodes and HSR lines as arcs. However, for any public intercity travel services, including HSR, trips essentially happen at two levels: the intracity level that includes access trip (from origin to departing traveling facility) and egress trip (from traveling facility to destination), and the intercity level (on-board travel). By representing cities as single nodes, the traditional arc-node model cannot capture the intracity portion, i.e., the access and egress trip segments, of an HSR trip. A significant part of HSR's accessibility advantage over other travel modes, such as air travel, however, often comes from the shorter access/egress time due to its more centrally located rail stations (Givoni 2006; Rodrigue, Comtois, and Slack 2016; Sun, Zhang, and Wandelt 2017). Failing to capture a complete picture of an intercity trip, the traditional arc-node framework falls short of offering an effective platform for accurately analyzing the accessibility of HSR service and evaluating the competitions among different intercity travel modes. This shortcoming of the traditional arc-node framework, as

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will be discussed in the next section, is further aggravated by the sprawling urban form of American cities.

Urban form and door-to-door based HSR accessibility

While research on HSR accessibility is abundant, accessibility analysis based on *door-to-door travel time* has not received the attention it deserves in HSR studies (Marti-Henneberg 2015). Most accessibility studies on HSR represent the city as a point and focus exclusively on on-board travel time. The truth is, however, HSR rarely provide door-to-door travel services by itself. Extra trip segments, such as access and egress trips, are often needed to supplement the on-board trip segment to complete the total journey. Both the access and egress trip segments happen at the intracity level and are influenced by the *urban form* of a city.

Urban form is a complex concept and its definition can vary in different disciplines (Clifton et al. 2008). From an urban and transportation perspective, urban form typically refers to the "shape, size, density and configuration of settlements" of urban places (Williams 2014). Among urban scholars there is a general consensus that American cities tend to be more spread-out than their counterparts in Europe and Asia (Dieleman and Wegener 2004). Because of the popularity of HSR development in Europe and Asia, it is no surprise that most HSR accessibility studies to date are carried out in European and Asian countries. While the relatively compact cities in Europe and Asia have made the traditional arc-node approach popular and led to the practice of considering only the on-board travel time in HSR accessibility studies, there has been an increasing shift in recent literature to include trip segments at the intracity level, i.e., access and egress trips. When it comes to HSR accessibility studies in the United States, the sprawling urban form of American cities makes it even more imperative to establish a comprehensive framework capable of incorporating access and egress trips.

There are three main reasons that make the omission of access and egress times especially problematic, and a more comprehensive framework is necessary to support HSR accessibility studies

in the United States. First, cities in the United States tend to be more spread out when compared to their counterparts in Europe and Asia. The sprawling nature of U.S. cities inevitably leads to longer overall access/egress time that will take up a higher proportion in the total journey time and make them difficult to be overlooked. Second, access/egress time varies spatially across each city. The actual access/egress time is determined by the locational information of trip origin, destination, and the traveling facilities. Neither of the above information can be represented in the traditional arc-node model since city is represented as single point. Given the sprawling nature of U.S. cities, accessibility improvement brought by a HSR system can vary significantly from city center to the peripheries. Access and egress times are thus crucial factors to reveal the spatial variations of HSR accessibility at the intracity level and should not be ignored. Finally, HSR will inevitably compete with air and auto at the intercity travel market due to their popularity in the United States. The exclusion of access and egress times fails to capture the total journey time and makes it difficult to directly compare HSR to air and auto intercity travel. In summary, the sprawling urban form of US cities, the popularity of existing air and auto intercity travel, as well as the increasing interests on HSR development in the United States warrant the need of an improved framework in HSR accessibility studies that are capable of incorporating the intracity segments of intercity trips. Such a framework will be especially pertinent to the U.S. context and will be capable of more accurately revealing the accessibility impact of a HSR system at finer spatial scales.

For a better evaluation of the accessibility benefit brought by a HSR system in the context of U.S. cities, a door-to-door travel time framework is thus needed to capture a more complete and accurate picture of the total travel time of trips via HSR. With door-to-door travel time and urban form as the two main themes, detailed research questions of this research are introduced and elaborated in the following section.

Research questions

       This research argues the sprawling nature of U.S. cities makes it imperative to establish a more comprehensive HSR accessibility framework to better evaluate how HSR will perform in conjunction with the unique spatial characteristics of American cities. Aiming at developing a more accurate evaluation of the accessibility benefit of HSR, this research will tackle the following research questions.

1) An intercity journey is usually composed of movements at both the intracity and intercity levels. What are the key components in each level and how do they determine the total travel time of door-to-door intercity journeys on different travel modes, such as HSR, air, and auto? How can these components be effectively modeled to derive a more accurate estimate of door-to-door travel time for a more realistic comparison of different travel modes?

2) The intracity segments (i.e., access and egress trips), which have been omitted in traditional HSR accessibility analysis, present an inseparable part of an intercity travel from a door-to-door travel perspective. There is a general understanding that the urban form of a city may influence the travel time of access and egress trips in the city. However, limited efforts have been dedicated to examining their relationship directly. How can the urban form of a city and the choice of a traveling facility location impact access/egress time? What will be an effective way to provide a quantitative representation for urban form and overall access/egress time, and perform a systematic investigation on their relationship?

3) HSR accessibility studies have rarely been carried out in the U.S. context. Using the proposed Dallas-Houston HSR project as an example, how could the proposed door-to-door framework be applied in the corridor and contribute to HSR accessibility studies in the United States? Given the popularity of air and auto for intercity travel, how can the proposed framework contribute to a better understanding of the spatial variation of the accessibility advantage of HSR for intercity travel when facing competition from these transport modes? As two of the

fastest-growing urban areas in the United States, what are the spatial development trends of urban form in the past decade for Dallas and Houston, and what are their implications on HSR development in the region?

Significance

With a paucity of literature on the study of intercity accessibility based on door-to-door travel time, this research will develop a door-to-door travel time framework that simultaneously integrates both the inter- and intra-city trip segments of a trip and provides more accurate accessibility analyses of intercity travel via HSR and other transport modes. The proposed framework will also incorporate the impact of urban form in HSR accessibility studies and investigate what kind of urban form may lead to accessibility advantage of HSR at the intracity level. Given the sprawling urban form of American cities, an in-depth investigation exploring the relationship between access/egress time and urban form will also reveal the role of urban form in affecting access/egress time. By revealing the impact of urban form – especially sprawling ones – on accessibility improvement associated with HSR, the results of this research can help urban and transportation planners better evaluate the accessibility benefit of HSR in the U.S. context.

Besides the theoretical exploration, this research will also implement the framework to the proposed Dallas-Houston HSR project to demonstrate the feasibility of the framework in HSR accessibility studies. Moreover, the Dallas-Houston case study is expected to further illustrate how the framework can be used to 1) identify areas within the cities where HSR holds accessibility advantages over competing transport modes, and 2) investigate the spatial trends of urban form development in Dallas and Houston and their implications on HSR development in the corridor.

While abundant in European and Asian countries, HSR accessibility studies have rarely been conducted in the U.S. city context. With the construction started on the California HSR line and numerous other HSR projects proposed in the United States, there are urgent needs to improve both the theoretical and empirical aspects of HSR accessibility studies that are suitable for the U.S.

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context. By investigating the listed research questions, this research will make contribution to both the theoretical and empirical grounds of HSR accessibility studies, especially as it relates to HSR studies in the United States. The results from the empirical studies can help regional and local transportation authorities by demonstrating more detailed accessibility patterns at the sub-city level. Results of the development trend analysis of urban form can also help urban and transportation planners understand the implications of current urban development trends on potential HSR development in the United States.

CHAPTER II

LITERATURE REVIEW

With the increasing popularity of HSR development in recent decades, HSR studies are

attracting more attentions among transportation and urban scholars. Emphasizing the potential for

HSR development in the United States, this chapter first provides an overview of the definitions

and current status of HSR in the country. Being intrinsically an accessibility study, a

comprehensive exploration on accessibility studies is then provided. Specific focuses are given to

HSR accessibility studies at both the inter- and intra-city levels. With urban form as a major

theme of this research, the final part of this chapter is devoted to the discussion of urban form,

i.e., the differences in urban form between American and European/Asian cities, and its impact on

modal competition and HSR development in the United States.

HSR development in the United States

The United States defines HSR in a slightly different way from European countries. The

International Union of Railways (UIC, or *Union Internationale des Chemins de fer* in French) and

European Union define HSR as a *system* that includes aspects of infrastructure, rolling stock, and

the compatibility of the two (UIC 2015). The infrastructure for newly built HSR services shall be

able to accommodate services with speed that are generally equal to or greater than 250 km/h,

while upgraded HSR lines shall be able to support services that are 200km/h or higher. The

definition of HSR in the United States adopts a different scheme by considering trip lengths as

well. The Federal Railway Administration, or FRA (2009) in the United States defines three

categories of HSR and Intercity Passenger Rail based on both the speed of the services and the

distance between major population centers the HSR lines serve: HSR-Express refers to HSR

services with top speed of at least 150 mph (240 km/h) on dedicated tracks that serve population

centers 200-600 miles (320-965 km) apart; HSR-regional refers to HSR services with top speed

of 110-150 mph (175-240 km/h) that serve population centers 100-500 miles apart; and Emerging

HSR services with speed up to 90-100 mph (145-175 km/h) that serve population centers 100-500

miles (160-800 km) apart.

HSR networks can be developed in a hub-and-spoke pattern or in a corridor-specific

pattern. When HSR is built in large scales, hub-and-spoke patterns are usually more popular with

large cities serving as major hubs (e.g., Paris, Madrid, Beijing, etc.) and secondary cities

connected to hub cities by spokes (Levinson 2012; Wu, Nash, and Wang 2014). However, at its

initial stages of development, HSR construction is more likely to follow corridor-specific

development patterns, especially in areas where conventional passenger rails do not yet claim

significant share of intercity travel market.

Being at the initial stage, existing and proposed high-speed rail development in the

United States largely follows a corridor-specific pattern. For example, the Acela Express,

Amtrak's high-speed rail line, operates along the Northeast Corridor (NEC) following a linear

layout and serves Washington D.C., Philadelphia, New York, and Boston along other

intermediate stops. The top speed of the service is 150 mph (240 km/h), and it remains the only

HSR service in operation in North America as of late 2017. However, there has been an

increasing amount of attention devoted to the possibility of adopting HSR as a new intercity

travel mode at the federal, regional, and state levels. With the enactment of the American

Recovery and Reinvestment Act of 2009, the Obama Administration committed $8 billion to

possible HSR projects in 13 corridors across the country. The increasing attention HSR receives

in the past decade also results in actual and proposed HSR development in the United States. For

example, construction of a state-wide HSR system has already started in 2015 and is expected to

connect Los Angeles and San Francisco with speed up to 200 mph (320 km/h) by 2029 (CAHSR 2015). Multiple other HSR projects, including the Dallas-Houston route, Baltimore-D.C. route, Miami-Orlando route, etc., have also been proposed across the United States. The recent progress of HSR development in the United States warrants detailed and accurate analyses of the benefits a HSR system can bring. Improved accessibility, which is often considered one of the most important benefits of HSR and helps it win political and public support, is on the priority list for close scrutiny.

Accessibility study

HSR offers high-speed intercity travel service and is expected to increase the accessibility of the cities it connects. As a key concept in the field of transportation geography (Van Wee 2016), the term *accessibility* has long been in the vocabulary of urban and transportation planners and often shows up in generalized statements of planning goals (Handy and Niemeier 1997). Depending on different planning and research goals, accessibility can be defined differently. Some general definitions of accessibility in transport planning include "what and how can be reached from a given point in space" (Bertolino, Clercq, and Kapoen 2005, 207), "the potential of opportunities for interaction" (Hansen 1959, 73) and "the potential to reach spatially dispersed opportunities" (Páez, Scott, and Morency 2012, 141).

Accessibility is determined by multiple factors such as the spatial distribution of the destinations, the ease of reaching the destinations, and the magnitude (e.g., population, GDP, etc.) of each destination (Handy and Niemeier 1997). Geurs and Van Wee (2004) list four types of components in the analysis of accessibility, including 1) the land-use component that reflects the amount, quality and spatial distribution of opportunities at each destination, 2) the transportation component that represents characteristics of the transportation network, 3) the temporal component that reflects the temporal constraints, and 4) the individual component that represents the needs, abilities, and opportunities of individuals. Geurs and Van Wee (2004) argue that even

though an accessibility measure should ideally take all components into consideration, applied measures usually only focus on one or more of the above components.

Handy and Niemeier (1997) list three types of popular accessibility measures, which include the cumulative opportunities measure, the gravity-based measure, and the utility-based measure. The cumulative opportunities measure is the simplest one by counting the number of opportunities reached within a given travel time. All potential destinations are weighted equally within the cutoff value, regardless of differences in travel time and opportunity qualities. The gravity-based measure is a more complicated measure of accessibility by giving opportunities different weights. Impedance functions like power, Gaussian, or logistic functions are the most commonly used weighting schemes. The utility-based measure, also known as the logsum, interpret accessibility as the outcome of a set of transport choices (Geurs and Van Wee 2004). This approach incorporates travelers' behavior by including a choice set representing the probability of an individual making a particular choice. While the utility-based measure certainly offers some theoretical and empirical advantages, it also requires the support of comprehensive social-economic data of the individual or household to incorporate the choice set for travel behavior prediction.

Geurs and Van Wee (2004) provide another classification scheme of accessibility measures from a transport planning perspective. Four basic perspectives on accessibility measures, including 1) infrastructure-based measures, 2) location-based measures, 3) person-based measures, and 4) utility-based measures, are listed and discussed with a focus on their pros and cons. Infrastructure-based measures is useful when analyzing the overall performance of transport infrastructure. The focus of this type of methods is the infrastructure, while land-use component is often ignored. While infrastructure-based measures are relatively easy to carry out and interpret, the results can be misleading due to the exclusion of land-use component. Location-based measures take geographic characteristics of opportunities into consideration and have been widely used in urban planning and geographical studies. The cumulative opportunities measure

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and gravity-based measure both belong to this category. Person-based accessibility measures refer to the concept of time geography outlined by Hägerstrand (1970). Various constraints in a space-time context were incorporated into the traditional accessibility studies. Despite the theoretical advantages of this approach, operationalization of person-based measures still faces several challenges, including the collection of detailed individual-level travel data and computational intensity (Kwan 1998). Utility-based accessibility measures are defined in the same way as the approach from Handy and Niemeier (1997). The advantage of utility-based accessibility measures is that they estimate the accessibility at the individual level and consider both users' and modal characteristics (Vandenbulcke, Steenberghen, and Thomas 2009). This type of study is a popular theme in economic studies (Geurs and Ritsema van Eck 2001).

Páez, Scott, and Wheeler (2012) proposed a particular view on accessibility measures by focusing on their normative and positive aspects. Páez, Scott, and Wheeler (2012) notice that a large number of accessibility applications often assumed the transportation component based on conventions and less frequently on actual measures of travel behavior. One of the examples they gave is, in order to measure accessibility to bus stops, "the user must be able to get to the origin transit stop and from the destination transit stop in a reasonable amount of time (five minutes or 400 m distance is typical standard for walking)" (Beimborn, Greenwald, and Jin 2003). Páez, Scott, and Wheeler (2012) feel there is a necessity to investigate more on how far people are willing to travel instead of assuming based on conventions. In their literature, normative accessibility measures refer to "how far people ought to travel or how far it is reasonable for people to travel", whereas positive accessibility measures are defined based on "how far people actually travel" (Páez, Scott, and Wheeler 2012). The positive aspect helps planners and policy makers to understand the accessibility of the current situation, while the normative perspective helps to understand what the desired outcomes need to be. The normative and positive approaches are illustrative when used in tandem to test whether opportunities (e.g., hospitals, grocery stores, daycare centers, etc.) are within the comfort travel distance of each household unit.

The advancement in spatial technologies, especially Geographic Information System (GIS), and the increasing amount of available geocoded data has made GIS-based accessibility research popular (Kwan, Janelle, and Goodchild 2003). Kwan et al. (2003) examine recent advances in accessibility study in three intersecting dimensions: representation, methodology, and application. As Kwan et al. (2003) point out, most techniques represent areas and object entities as points and use them as origin-destination (OD) pairs in accessibility studies. This is especially true when GIS is used as the platform to calculate accessibility. Spatial scale can also significantly affect the analytical results, and point representation of OD pairs may not always be the best representation of cities depending on the spatial scales of actual studies.

Development of methodology in accessibility studies experience an increasing focus on the time-geographic perspective (Hägerstraand 1970) and the use of the space-time prism (Lenntorp 1977) in recent decades. By applying space-time constraints, accessibility measures witness a shift from place-based accessibility into individual-based accessibility. The popularity of location-aware devices makes collection of tracking data with both spatial and temporal attributes relatively easy and manageable with a limited monetary budget. The inclusion of the temporal aspect as a whole new dimension in transport accessibility study brings more ways of data analysis and visualization. For example, Fang et al. (2012) use a tracking data set that consists of 12,000 taxis in Wuhan, China to identify alternative bridge paths across the Yangtze River from the three existing bridges at various time periods (i.e., different time of the day and different day of the week). The advancement in information communication technologies (ICT) in recent decades also expands accessibility studies into both the physical and virtual space as virtual space is becoming an increasingly integral part of everyday life (Yu and Shaw 2008; Shaw and Yu 2009).

Applications of accessibility research encompass a variety of topics, such as connecting disadvantaged households to job markets (Wang and Minor 2002), analyzing accessibility to social services (Church and Marston 2003), evaluating public transit service using location-

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allocation and coverage models (O'Sullivan, Morrison, and Shearer 2000), examining

infrastructure vulnerability (Grubesic, O'Kelly, and Murray 2003), etc. Accessibility studies of

HSR are among the popular applications. HSR is often introduced as new/upgraded infrastructure

and is expected to increase both the overall accessibility of all cities in the network as well as the

accessibility of individual cities in the system. Aggregated accessibility measures, such as the

cumulative opportunities and gravity-based measures, are popular in HSR accessibility studies to

evaluate the overall benefit brought by a HSR. Location-based HSR accessibility measures, on

the other hand, are commonly seen to differentiate the accessibility improvement for specific

cities. While demonstrating theoretical advancement, accessibility studies of HSR from the

logsum and person-based measures are rare due to the lack of necessary data and the difficulty of

gathering them. HSR accessibility studies will be discussed in more detail in the following

section.

HSR accessibility: intercity and intracity accessibility

In the context of HSR accessibility research, reduced travel time is one of the most

important effects of HSR and helps it win political and public support (Yin, Bertolini, and Duan

2015). For example, Cascetta et al. (2011) found out that 71.2% of HSR users along the Rome-

Naples corridor claim that the reduced travel time is the main reason they choose HSR over other

modes of transportation. Therefore, HSR accessibility studies have in general shown a strong

emphasis on the reduced travel time aspect when evaluating accessibility improvement attributed

to a HSR system.

A complete and accurate representation of the reduced travel time aspect of a HSR

system, however, can be a complex and challenging task due to the nature of HSR travel. As a

form of public transportation, HSR rarely delivers door-to-door travel services by itself. The total

travel time of a typical journey by HSR includes multiple major components, such as access time,

on-board travel time, and egress time. Access time represents the time the traveler needs to get to

the traveling facilities (e.g., HSR station) from the origin of the journey (e.g., home location, office location, etc.) in the departure city; on-board time is the time a traveler spends on the moving vehicle; and the egress time stands for the travel time needed to get from the arrival facility to the final destination of the journey. Access and egress trips are usually achieved through other modes of transportation. The reduced travel time of a HSR system can result from either the inter- or the intra-city trip segments, or both. To capture HSR's full effect in reducing travel time, network consideration of HSR should ideally include both of the two inter-connected parts, i.e., the HSR (intercity) network and access to the HSR (intracity) network (Vickerman 1997). Existing literature, as will be shown below, has primarily focused on either the inter- or intra-city segments of the trip.

a. Intercity accessibility study

Since HSR services are generally designed to promote intercity rather than intracity connections, most of HSR studies are carried out at national/regional level and focus primarily on the intercity segment of the trip. Travel time and travel cost are considered as major indicators of impedance, measuring the ease of movement; cities that host HSR stations are perceived as origins and destinations that represent potential opportunities. Magnitude of opportunities is often weighted by total population or gross domestic product (GDP) of the city. Passenger flow data at railway stations can also function as a weighting factor when available. GIS is a common platform for data management, computation, and visualization in HSR accessibility studies.

Gravity-based measures are among the most commonly used methods in existing HSR accessibility research. Weighted average travel time/cost (WATT) and economic potential measures belong to this category. Impedance and attractiveness are two major components in these types of measures. Cites are usually represented as single points on the HSR network. Impedance is usually expressed in travel time/cost. Mass of city is represented as total population or GDP—the higher population or GDP a city has, the higher mass it possesses. The

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attractiveness between city pairs is positively related to the mass of the two cities and inversely related to the impedance.

Gutiérrez (2001) applies a set of accessibility indicators to model accessibility changes with and without new HSR lines in Europe that were expected to complete by 2005. Accessibility indicators, including economic potential, weighted average travel times, and daily accessibility, are applied in the study. All three indicators are based on travel time but are defined in different ways. Economic potential and weighted average travel time both consider all relationships within the study areas with equal weight, while economic potential applies a distance decay factor (cities that are further away have less impact). Daily accessibility has a cut-off value (e.g., maximum four hours) on travel time and only considers areas that fall within the threshold. Cities are represented as nodes on the existing European railway network and weighted by their population. Maps of accessibility changes generally show that the southern part of Spain benefits the most from the new HSR lines with 20% improvement on travel time while the rest of the covered area receives lesser improvement at around 2-5%. Monzón, Ortega, and López (2013) evaluate accessibility changes introduced by the HSR system in Spain with a focus on spatial equity. Chandra and Vadali (2014) apply the same set of accessibility indicators to evaluate accessibility impacts of the proposed America 2050 high-speed rail corridor with a focus on the Appalachian region. Martínez and Givoni (2012) determines winners and losers of UK cities with the introduction of the proposed High-Speed 2 (HS2) line in the UK.

The recent nation-wide development of HSR system in China provides an opportunity to explore the potential impact of HSR at a national level. For example, Cao et al. (2013) evaluate the accessibility changes under the impact of China's HSR network. Forty-nine pairs of cities, including major metropolitan areas, provincial capitals, and important central cities in particular regions are included in the accessibility analysis. ArcInfo is adopted for data management, visualization and calculation. Economic information, including population and GDP, is considered as attribute for each node. Intracity travel time and service waiting time are not

considered in this study due to fluctuation and data unavailability. The spatial distribution of weighted average travel time (WATT) by HSR for all the 49 cities shows that cities with higher accessibility scores are located mostly in the eastern and central region of China where several routes cross. A series of contour-based calculation, identifying daily accessible cities of each city within 2, 4, and 6 hours, are also performed. Comparison of city accessibility by HSR and airline is also carried out, demonstrating similar patterns with cities located in the central part of China having higher potential accessibilities. Jiao et al. (2014) employ similar accessibility measures to evaluate the impact of China's HSR in combination with the conventional railway system while expanding the result to 333 prefecture-level cities instead of the 49 major cities.

Shaw et al. (2014) add a temporal aspect of HSR accessibility study by classifying and comparing the accessibility of the Chinese rail services based on four important stages: 1) a stage with the traditional rail service (before August 2008); 2) a stage with HSR lines between 2009 and 2011; 3) a stage with reduced-speed HSR lines (between 2011 and 2012), and 4) a stage with several new HSR lines. The reason for the speed reduction in stage 3 is due to safety concerns to account for the Wenzhou HSR collision accident on July 23 2011. Train timetables including travel time, ticket price, and mileage data are derived from a public ticket website. Unlike the accessibility study by Cao et al. (2013), intra-station and inter station transfer time are estimated when calculating total travel time in this study. Travel time, distance, and cost for the four stages in China are calculated with collected data. The spatiotemporal pattern of travel time accessibility shows a slight decrease of in-vehicle travel time (from 26.685 h to 24.4 h) and an increase of out-of-vehicle travel time from 5.867 h to 6.088 h. This out-of-vehicle time, however, only refers to the train transfer time within a city. Access time, which refers to the time a traveler needs to get to a train station, is not included in this study. Results show that most of the cities experienced longer overall travel time due to the reduced speed in stage 3. Because of the elimination of some general train services, travel cost decreased by 15.10% even after the implementation of the ticket fare reduction policy on January 1, 2013. A radial pattern was observed with Beijing-Tianjin-

Hebei at the center with the best accessibility in China for both travel cost and distance accessibility.

A major drawback of most HSR accessibility studies, including those reviewed above, is that cities are viewed as single points, meaning only the on-board travel time (the time a traveler spend on rolling stock) is considered for HSR travelers. The truth is, however, HSR does not provide door-to-door travel services, and intracity/station-wide accessibility is also crucial to ensure short access time to train stations and total travel time. Depending on urban form and the availability of intermodal connection, access and egress trips may represent a significant portion of total travel time and should be incorporated in HSR accessibility analysis. This is especially true for most American cities where the degree of urban sprawl has been relatively high compared to European and Asian cities. Moreover, HSR is usually designed to provide short- to medium-distance travel. At this distance range, on-board travel time is usually short, making access and egress times take up a larger portion of the overall travel time of an intercity trip. The higher proportion of access and egress times make them difficult to be overlooked and in need of further investigation.

b. Intracity accessibility of HSR station

As most HSR accessibility studies focus primarily on the intercity part of the trip, the intracity accessibility of HSR station is often omitted. As Van der Spek (2003) points out, the HSR station is rather a "connector" to other forms of transportation and functions. Poor station accessibility can greatly impair the accessibility advantages of the HSR system. The Gifu-Hashima station in Japan as well as the HSR station in Avignon, France are examples where poor station connectivity greatly reduces the usage of the service (Sands 1993; Todorovich, Schned, and Lane 2011; Yin, Bertolini, and Duan 2015).

HSR station accessibility has a direct impact on access and egress times that can potentially be a significant portion of the total travel time. HSR stations are usually positioned

near city centers and thus require less access/egress time when compared to airports. For example, Román and Martín (2011) find out that for 91% train travelers, access time to train stations was significantly lower than it was to airports in the Madrid-Barcelona corridor in Spain. Another reason that makes station accessibility even more important is that HSR stations are usually sparsely located due to the compromise of high speed. To maintain short travel time, HSR usually have less intermediate stops than traditional rail services to reduce time spent on slowing down and stopping. Any new stations added will be a trade-off between tapping new markets and loss of market share in major cities due to increased overall travel time (Vickerman 1997). Marti-Henneberg (2015) calculates based on data from the UIC website that Italy has one HSR station per 132 km HSR track, France 119 km, and Spain 84 km.

A long length per HSR station means there will most likely be only one HSR station to serve the majority of a city. Even at times when multiple HSR stations are present in hub cities, each of the stations is usually designated to serve a particular region and the different stations in the same city will not be interconnected. For example, Paris has 6 major train stations but each of the stations is positioned to serve certain regions of France and Europe (Freemark 2009). To get to a certain destination, the traveler has to choose the station that serves the specific region instead of simply picking the closest facility.

While scholars in general agree that accessibility of HSR stations is important to the success of a HSR system, research on station-wide accessibility has not received the attention it deserves when compared to the study of HSR accessibility at the intercity level (Marti-Henneberg 2015). Station-wide accessibility is usually considered as an ancillary part in HSR accessibility studies at the intercity level, and it is common practice to estimate access/egress time in an aggregated way for an entire city without differentiating access/egress time variations across the city. For example, Chen, Correia, and de Abreu e Silva (2015) calculate a series of accessibility indicators to measure potential regional economic development effects of HSR in Spain. Their research incorporates access time to train station and represents the total travel time by HSR as

the sum of access time (i.e., the travel time by car from the centroid of the origin municipality to the nearest station), on-board travel time, and egress time (i.e., the travel time by car from the arrival HSR station to the centroid of destination municipality). While access and egress times to train station are included in their study, cities are represented as centroids, which stands for the geographic center of the city and is not always a good representation of the center of the actual population or employment distribution.

Zhong, Bel, and Warner (2014) carry out a comparison study between the Los Angeles-San Francisco HSR route in California and the Madrid-Barcelona HSR route in Spain. The authors choose a modified version of Metropolitan Statistical Areas (MSA) and Consolidated Statistical Areas (CSA) as the study areas of the two cities in the United States and the Provinces of Barcelona and the Province of Madrid as the study areas in Spain. Cities are, in their analysis, viewed as areas rather than simple nodes. The subunit for the analysis is municipality and district for the Spanish cities and Zip Code Tabulation Areas for the California cities. An aggregate score is derived based on population, population density, employment, and relative income simultaneously for each subunit to represent its unique characteristics. Maps of the aggregated score reveal that both of the Spanish cities have high levels of concentration, while the California cities have less distinguishable centers.

Station accessibility is also carried out for the existing HSR station in the Spanish cities and the proposed HSR station in the two California cities in their study (Zhong, Bel, and Warner 2014). Catchment areas are delineated using circles with 5 km, 10 km, and 25 km radius around each HSR station. Results from the accessibility analysis of the stations show that a 10 km radius around HSR stations in the Spanish cities can already cover most potential HSR riders, while a 25 km radius will still leave out a considerable portion of potential HSR riders in the California cities. While this paper demonstrates that urban form plays an important role on HSR station accessibility within cities, it does not further investigate systematically how urban form can

impact the accessibility of HSR station, which will require more than a comparative study with two pairs of cities.

A direct finding from the review of intracity HSR station accessibility is that urban form is closely related to HSR station accessibility. When studying HSR accessibility in the U.S. context, low-density development patterns of American cities can be even more detrimental to the success of HSR projects. The unique characteristics of American cities in terms of urban form and their impact on HSR development as a mode of public transportation will be the focus of the next section. A modal competition perspective among HSR, air and auto travel will also be mentioned as a much-needed approach in HSR accessibility studies in the U.S. context.

Urban form, modal competition, and HSR accessibility

Urban form refers to the physical characteristics of the built-up areas, including the shape, size, density, and configuration of settlements (Williams 2014). Two distinguished and opposite urban forms, a compact city and a sprawling city, have received constant attention from both urban scholars and planners. In short, compact urban form is represented by high-density development and multi-functional land use pattern, while urban sprawl is characterized by low density, single-use land pattern, and strip and leapfrog development (Dieleman and Wegener 2004). While it is still under much debate whether compact or dispersed urban development pattern represents a better urban form (Burton 2000; O'Toole 2001; Schwanen, Dijst, and Dieleman 2004), there is a general consensus that American cities tend to be more spread-out than cities in Europe and Asia (Figure 2.1).
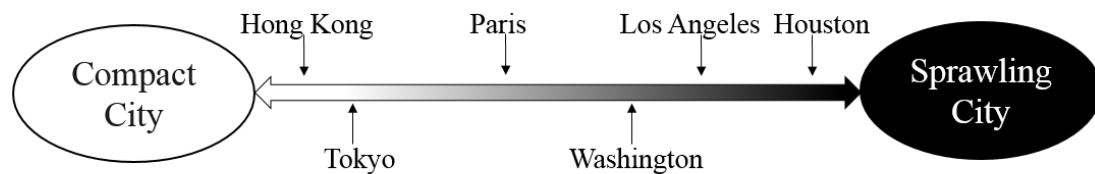

Figure 2.1 Typical urban forms of world cities. Data adopted from Bertaud and Malpezzi (2003).

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It is suggested in existing literature that different types of urban form have a direct impact on HSR performance. Yin, Bertolini, and Duan (2015) examine and summarize the cross-country comparison of HSR modal share and find it obvious that the traffic volume generated and substituted by HSR is highly country-specific. For example, modal share of HSR in Spain, France, and Japan meets or exceeds ridership forecast, while HSR passenger numbers in Germany fall short of expectation. According to Vickerman (1997), two of the key reasons for Germany's lower-than-anticipated use of HSR include 1) a lot of German cities lack the monocentric urban form like French cities have, and 2) the extensive highway system (the autobahn) in Germany makes automobile travel popular. Vickerman's conclusion makes it clear that urban form as well as modal competition have significant impact on the success of HSR. Cities in the United States also observe the two characteristics Vickerman lists to a larger extent. In fact, Thompson (1994) lists low population density and relatively low cost of air and automobile travel compared to that in European and Asian countries among the major reasons HSR had not been successful in the United States.

Kwan and Chai (2015) compare the urban form, car ownership, and activity space of Beijing and Chicago to explore the differences between Chinese and American cities. Urban form is measured by distance from residence to urban centers, population density, and density of retail facilities, while activity space is measured by generating a minimum convex polygon using the Minimum Bounding Geometry tool in ArcGIS based on out-of-home activity locations. Results show that high levels of activity space are achieved in Beijing by high-density development and accessibility to public transit, while in Chicago it is achieved by roadway density. The finding reinforces the general perception that U.S. cities, represented by Chicago, depend heavily on the automobile and have much lower development densities than that in the Chinese cities.

Shuai (2005) evaluates the economic relationship between traditional central business districts (CBDs) and suburb centers in eleven Virginia metropolitan statistical areas (MSA) and finds that traditional CBDs are no longer the driving forces of growth, and suburbs are on the

verge of becoming the leaders to promote economic growth. Ewing, Pendall, and Chen (2003) explore the different measurements of urban sprawl and their impacts on the transportation system. Four factors, including residential density, neighborhood mix of homes, jobs, and services, strength of centers, and street network accessibility are considered when measuring sprawl. Results from the multiple regression analysis reveal that regions with high levels of compactness outperform sprawling ones for most travel and transportation outcomes. Cities including New York, San Francisco, Boston, and Portland are among the most compact ones, while Atlanta, Raleigh-Durham, and Riverside-San Bernardino belong to the opposite side.

It is no secret that urban sprawl favors automobile travel over public transportation and can be detrimental to the efficiency and even the existence of public transportation. Sinha (2003) discusses the relationship between public transportation and urban form for cities in the United States. According to Sinha (2003), American cities generally grew around one urban core surrounded by multiple layers of high-density concentric rings up until World War II. The newly built highways in the 1950s changed this pattern dramatically. With the newly built highways reaching out to the country and the housing programs encouraging single-family housing, a leapfrogging phenomenon gradually overtook the traditional growth pattern in most urban areas. Automobile also played its role in accelerating this process. The low-density of metropolitan areas made per unit cost of infrastructure, including road maintenance, sewers, water lines, etc. significantly higher. Public transit is among the victims of suburbanization. The low-density metropolitan areas made it impossible for public transit to stay in business and had to seek public acquisition to provide highly subsidized services. While in recent years the idea of the utilization of public transportation to improve sustainability has become increasingly popular, population and land use patterns largely remain the same and the automobile is and will likely remain the dominant choice of transportation for most Americans in the near future.

Not only will urban sprawl reduce the attractiveness of HSR as a form of public transportation, the popularity of automobile travel will also put HSR in a more disadvantaged

spot from a modal competition perspective. Most studies focus on competition between HSR and air, leaving out automobile travel as a competing intercity travel mode. In the United States, however, automobile travel is popular for short- and up to medium-distance travel and needs to be considered from a competitive aspect in HSR accessibility studies. One of the major obstacles to compare HSR and automobile travel is the different nature of the two modes—HSR is a form of public transportation while automobile travel comes largely from private driving. This also means that unlike HSR and air, automobile delivers door-to-door services. A door-to-door travel time approach, which this research will propose, then becomes a prerequisite to enable modal competition analysis across the three modes.

In conclusion, cities in the United States in general observe dispersed development pattern that can be potentially detrimental to HSR accessibility. The heavy dependence on automobile travel also raises challenges to the successful implementation of HSR. Considering the huge investment HSR systems require, it is necessary to research the relationship between urban form and accessibility of HSR station in more details in the U.S. context. Given the popularity of air and auto intercity travel, a modal competition perspective is also required for more realistic illustration of how much accessibility benefit a HSR system can bring in the United States.

Summary

The literature review shows that there are several gaps in existing HSR accessibility studies, especially for studies applied to U.S. cities, and they are summarized as follows.

1. HSR accessibility studies are generally carried out either at the intercity level or the intracity level. However, a door-to-door approach, which can incorporate both the intercity and intracity segments of a trip via HSR, is much needed to provide a more complete picture of HSR trips and more realistic assessment on accessibility changes brought by HSR service to a city.

2. While there is a consensus that low-density development is harmful to HSR's success, little effort has been dedicated to a systematic study in the relationship between urban compactness and HSR accessibility. An in-depth analysis between the two will lead to a more thorough understanding of how urban form may impact HSR accessibility and contribute to a better assessment on the likelihood of successful HSR implementation in a city.

3. There is a lack of literature devoted to the analysis of modal competition between HSR and automobile as intercity travel modes. In many U.S. cities, the automobile is the dominant mode for intercity travel and provides door-to-door service. When HSR is introduced as an alternative for intercity travel, it will face inevitable competition from the automobile. How well will HSR compete with the automobile in providing a door-to-door service? Further analysis based on a door-to-door travel time measures will be needed.

4. Most HSR accessibility studies are carried out in European and Asian countries. The unique characteristics of U.S. cities warrant in-depth studies focusing on HSR issues in the U.S. context. This will not only help fill the regional gap, but also help urban and transportation authority gain further understanding on the challenges and opportunities of HSR development in the United States.

CHAPTER III

THEORETICAL FRAMEWORK AND METHODOLOGY

There has been a push to adopt a door-to-door travel time approach in HSR accessibility studies to capture a more complete and accurate representation of total journey time (Peer et al. 2013; Salonen and Toivonen 2013; Marti-Henneberg 2015). As suggested by the literature review chapter, accessibility studies of intercity travel usually represent cities as single points and are capable of incorporating only the on-board travel time. However, cities are areas and access and egress times at the intracity level are inseparable parts of an intercity trip. A door-to-door travel time framework, which will be proposed and defined in this chapter, offers a more comprehensive representation of total travel time by simultaneously incorporating trip segments at both the inter- and intra-city levels.

While this dissertation tackles three relatively independent but related problems in HSR accessibility studies, the research methods used to solve these problems are all based on the door-to-door travel time framework and they share certain methodology approaches. This chapter will focus only on the shared framework and methodology, while leaving out the unique approaches of each individual piece in its corresponding chapter.

A door-to-door travel time framework

HSR accessibility studies have traditionally been conducted using the arc-node framework where cities are represented as single points and HSR lines as arcs. Such an approach is capable of focusing only on the on-board travel time at the intercity level, while leaving out

trip segments at the intracity level such as access and egress times. To provide a more complete

and realistic representation of the total journey time of HSR travel, this research proposes a door-

to-door travel time framework that identifies and incorporates the following key components for

intercity trips at both the inter- and intra-city level simultaneously (Figure 3.1). Specifically,

door-to-door travel time in the figure represents the overall door-to-door travel time for intercity

trips; access time represents the time a traveler needs to get to the traveling facilities (e.g., rail

stations, airports, etc.) from the starting point of the journey (e.g., home location, office location,

etc.) in the origin city; waiting time is a combination of the time a traveler spends on check-in,

security check, and actual boarding; on-board time is the time a traveler spends on the moving

vehicle; transfer time refers to the time a traveler spends at the arriving facility before being

picked up by an egress mode; and egress time stands for the travel time a traveler needs to get

from the arriving facility to the final destination, usually through another mode of transportation.

Access time and egress time are also widely known as the "first mile" and "last mile" in public

transportation studies (Vespermann and Wald 2011). Waiting time can be generalized by the time

a specific mode requires its passengers to arrive before the actual departure time (e.g., 30 minutes

for HSR, 60 minutes for air). Transfer time is largely dependent on the interconnectivity of the

specific traveling facilities.
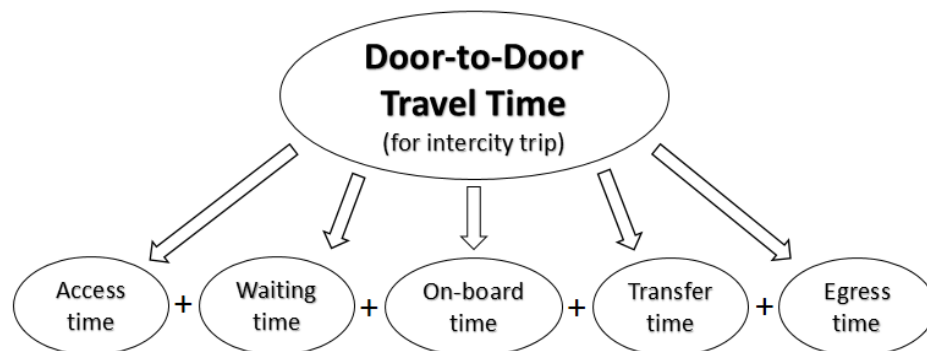
Figure 3.1 Key components of intercity trips to represent door-to-door travel time.

A primary focus of this research is the urban form's impact on access and egress times. Access and egress times vary spatially depending on the origin and destination of the trip as well as the location of traveling facilities. Egress time can be approximately regarded as a reverse process of access time for a specific city. For example, the *egress* time in City B during the intercity travel from City A to B is a reverse process of the *access* time in City B in intercity travel from City B to A. Since the access and egress times will be basically identical for the same city, they are referred as *access/egress time,* or simply *access time* throughout this study.

For air and HSR travel, a journey will always have all the components; for automobile travel, on-board time is usually the only component as automobile travel delivers door-to-door travel. The absence of access and egress times makes it difficult to consider automobile travel when evaluating urban form's impact on access and egress times. To solve the problem, this research divides automobile intercity travel into multiple segments so that it can be incorporated in a similar fashion as rail and air travel. The conversion process will be discussed later in the methodology part.

Methodology

This research adopts a set of quantitative approaches to analyze the impact of urban form on access/egress time of intercity trips based on door-to-door travel time. This section will discuss 1) representation of city and automobile travel, and 2) choices of measurements for urban form and access/egress time.

a. Representation of city and automobile travel

In order to incorporate access/egress time as part of the door-to-door framework, it is necessary to represent a city as an area rather than a single point to get different access/egress time for trips with origins and destinations at different locations. Moreover, the lack of access/egress time from automobile travel also makes it difficult to compare auto to HSR and air

travel under the door-to-door framework. Therefore, specific models and treatments are proposed to tackle these two issues.

i.   City as urbanized area

In order to measure door-to-door travel time, a city needs to be represented as an area as opposed to a single point. The boundary of city, depicting the targeted service area of intercity travel modes, needs to be drawn or picked based on existing representations of cities. According to the FRA's delineation of the targeted service area of potential HSR corridors, the term "population centers" are used to describe where potential passengers are located (FRA 2009). Referencing the FRA's depiction, this research chooses urbanized area to represent cities in the United States in this study. According to the U.S. Census Bureau website, urbanized area "comprise(s) a densely settled core of census tracts and/or census blocks that meet minimum population density requirements, along with adjacent territory containing non-residential urban land uses as well as territory with low population density included to link outlying densely settled territory with the densely settled core" (U.S. Census Bureau 2010). One of the major criteria of urbanized area is that it refers to *urban area* with total population over 50,000. The high population density of urbanized area by its definition makes it a good representation of population centers and the service areas of a HSR system.

ii.   Conversion of automobile travel

Automobile travel is a popular travel mode in the United States for short- to medium-distance intercity travel. Unlike HSR and air transportation, automobile travel does not require travelers to go through public traveling facilities (e.g., rail stations, airports) and delivers door-to-door travel services on its own. This makes it difficult to extract access and egress times from automobile travel to compare that from HSR and air travel under the door-to-door framework. In this research, intercity automobile travel is divided into three segments so that it is modeled in a format similar to HSR and air travel with access trip, on-board trip, and egress trip.

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A concept of *converging point* is introduced to replace the term of traveling facility in this study. Converging point (CP) represents the point where all travelers in the origin or destination city converge before they reach a shared intercity travel path. For HSR and air travelers, converging points are the traveling facilities, i.e., HSR stations and airports. For intercity automobile travel, a major highway usually serves as the main connector of the two cities. Although there is no mandatory converging point for auto travel at the intercity level, a deeper examination on the shortest routes of intercity auto travel from all origin-destination pairs reveal that the routes do converge at highway entry points. An illustration of the concept of CP for automobile travel is provided based on the Dallas and Houston corridor (Figure 3.2). Shortest paths from each census block group in the Dallas-Fort Worth area to each census block group in Houston are calculated and mapped out in a GIS environment. The map shows all automobile trips from the DFW area converge at the green dot near Dallas first (equivalent to access time), spend a significant amount of travel time on the major connector (equivalent to on-board travel time of HSR and air travel), and finally diverge at the green dot near Houston to reach final destinations (equivalent to egress time). The purple line represents a segment of Interstate 45 that functions as the major connector of the two cities; the two green dots at both ends represent converging points for the two cities, respectively.

Based on the concept of converging point, intercity auto travel can be divided into three segments, including access time to the converging point in the origin city, time spent on major connector highway (equivalent of on-board travel time from HSR and air travel), and egress time from the converging point in the destination city to the final destination. With the introduction of CP, one distinct characteristic of the three intercity modes, namely HSR, air, and auto, lies in the locations of the CP in relation to city center. For HSR, CPs are HSR stations and typically located close to city center to deliver fast city center to city center travel; for air, CPs are airports and usually located at city peripheries due to the characteristics of airports (e.g., noise, need for large

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Figure 3.2 Auto converging points between Dallas and Houston.

area of land, etc.); for auto, CPs are usually the entry/exit points of the major highway connector

between the cities and are located outside of the city.

b. Measurement of access/egress time and urban form

There is a general consensus among researchers that less compact cities usually lead to

higher overall access time to public traveling facilities in a city. However, limited effort has been

dedicated to an in-depth investigation on the relationship of urban form and access time. Relying

on a quantitative approach, this study aims to develop quantitative measures to describe the

compactness of urban form and the average access time to a transportation facility in the city, and

provide a systematic examination of their relationship.

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Accessibility studies are often carried out at aggregated levels rather than individual level due to data availability. For example, the transportation analysis zone (TAZ) is a commonly used subunit when performing urban transportation analysis. Similarly, this study divides an urbanized area, which represent the city area and the study area of this study, into subunits (i.e., block groups) for calculating localized access/egress time as well as for measuring the distribution of population within the urbanized area. This research chooses the following methods to represent access/egress time and urban form.

i.   Weighted average access/egress time

Access/egress time is directly affected by urban form and is a main focus of this research. Weighted average travel time has been used frequently in accessibility studies (Gutiérrez 2001; Diao, Zhu, and Zhu 2016; Jiao, Wang, and Jin 2017) and provides an overall measurement of travel time in an area to a specific location. This research uses weighted average access time (WAAT), which is based on weighted average travel time, to provide an overall measure of a city's access time to converging points of each mode. WAAT can be calculated as

$$WAAT = \frac{\sum_y(T_{xy} \times P_y)}{\sum P_y} \qquad (3.1)$$

where x represents the location of the CP, y represents the individual people in a subunit of the urban area (e.g., census block groups), T_{xy} represents travel time between each people to the traveling facility, and P_y represents the total count of people in a subunit of the urban area. For different travel modes, CPs are likely located at different subunits and will result in changes of the location of x.

ii.   Standard distance as a measure of urban compactness

Just like standard deviation is a statistic that represents the distribution of data values around the statistical mean, standard distance (SD) measures the level of compactness or dispersion of a group of points around their mean center. Standard distance can be calculated as

$$SD_w = \sqrt{\frac{\sum_{i=1}^{n} w_i(x_i - \bar{X})^2}{\sum_{i=1}^{n} w_i} + \frac{\sum_{i=0}^{n} w_i(y_i - \bar{Y})^2}{\sum_{i=1}^{n} w_i}} \qquad (3.2)$$

where $(\bar{X}, \bar{Y})$ stands for the mean center of a cluster of points, (x_i, y_i) represents the location

coordinate of each point, and w_i is an optional weighting factor for each point.

An important note when using standard distance as a measure of urban compactness is

that results based on standard distances are only comparable when applied to areas that

encompass similar amount of total population. For example, it will be misleading to compare the

standard distance of a place with 50,000 population to a place with 5,000,000 population: even

though the place with the much higher population will probably generate a larger standard

distance, it does not necessarily mean the city with 5,000,000 population is less compact – it is

mostly likely because the city needs more space to accommodate the larger population. So when

standard distance is used as a measure of urban compactness for comparison reasons, it is

important to make sure the cities in the comparison have roughly the same total population.

With rail stations traditionally located at or near city centers, a commonly accepted idea

is that rail transportation will have advantages over air transportation by offering shorter access

and egress times. The shorter access/egress times results from relatively central locations of rail

stations, however, is based on the assumption that trips will start and end at or near city centers.

While this might be true for cities in Europe and Asia where urban areas observe compact and

high-density development, cities in the United States have been known for dispersed and low-

density development patterns. Urban sprawl, suburbanization, and the lack of strong city centers

will likely reduce or even negate the advantage of centrally located rail stations over airports in

terms of access/egress time. Therefore, a door-to-door based approach, which incorporates both

the inter- and intra-city segments of intercity trips, will be able to provide a more realistic

evaluation of the performance of the various transportation modes for intercity travel. Since

access time is heavily dependent on urban form, an in-depth investigation is needed to explore the

relationship between certain characteristics of urban form and access time to travel facilities of different intercity travel modes, such as HSR, air, and auto.

With access/egress time and urban form measured and quantified using the above methods, a natural next step is to explore the relationship between the two to reveal the impact of urban form on access/egress time. Specific procedures and implementation of the analysis on the relationship between access time and urban form will be discussed in detail in the following chapter.

CHAPTER IV

EXPLORING THE RELATIONSHIP BETWEEN ACCESS TIME AND URBAN FORM

Based on the door-to-door travel time framework and the methodological approach presented in the last chapter, this chapter examines the impact of different urban forms on access time of multiple intercity travel modes (i.e., HSR, air, and auto) from a modal competition perspective. A simulation-based model is used for easy control of certain characteristics of urban forms. After outlining the detailed specifications of the simulation model, results and discussion are presented to reveal the roles of urban form on access time from the different travel modes.

Simulation is a popular and efficient way to test theories and models in transportation studies with relatively low or no data collection requirement. For example, Farber et al. (2013) construct multiple concentric and polycentric models and simulations to explore the relationship between urban form and social interaction potential of metropolitan regions from a time-geographic approach; Páez, Farber and Wheeler (2011) adopt a simulation-based approach to test the applicability of geographically weighted regression as a method to investigate spatially varying relationships. In this study, simulation provides the flexibility to control a set of parameters in different scenarios. This research constructs a set of synthesized cities to represent urban forms with varying characteristics while keeping certain parameters the same, i.e., all scenarios share the same size, shape, mean city center, while the spatial distributions of population are different. Measurements based on the synthesized cities are then imported into regression analysis to explore the relationship between access/egress time and the spatial characteristics of the city.

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Simulation setup

A set of grid-based synthesized cities is generated to represent monocentric urban forms with different levels of compactness (Figure 4.1). The synthesized urban form scenarios aim to provide a gradual change in urban compactness through varying spatial distributions of population. These scenarios range from highly compact patterns to highly decentralized ones. More details about the synthesized urban forms are as follow.
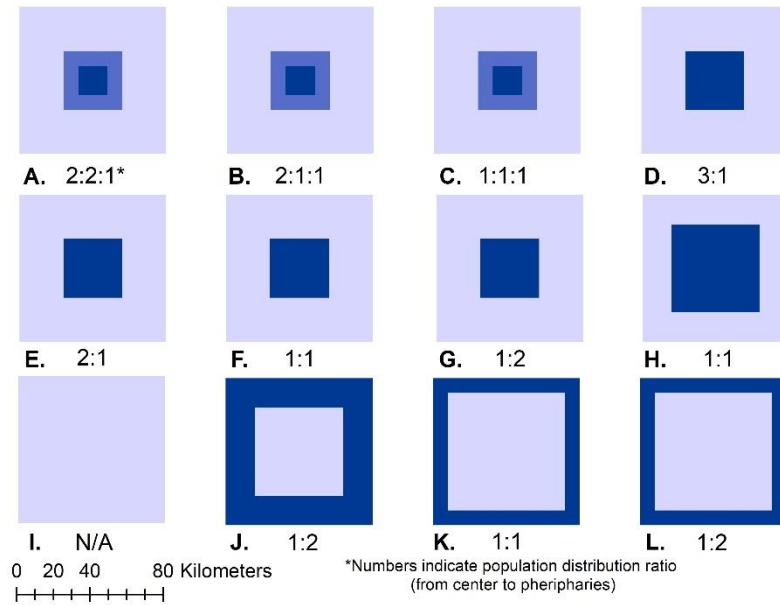
Figure 4.1 Synthesized cities with different distribution of population.

- Each city is composed of a total of 10×10 grids, and each grid is a 8 km × 8 km square and together form a total area 80 km by 80 km urban area;

- A total population of 1,000,000 (10,000 per grid on average) is assumed in the region;

- The spatial distributions of population range from concentrated urban form with high density at the center to scenarios with high density at the periphery, while the mean centers of population are kept at the geographic center of the synthesized cities.

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- For each synthesized city, the ratio of population in areas with different shadings, from the geographic center of the city to the periphery, is listed below the corresponding figure (Figure 4.1). For example, for scenario A, a population ratio of 2:2:1 indicates 40% of the population are allocated in the inner square, another 40% in the square ring in the middle, and the final 20% in the outer ring.

- A constant 60 km/h movement speed is assumed across the urban area.

An important distinction among HSR, air, and auto intercity travel is their conventional location of a converging point in relation to the city center (see the Methodology section under Chapter III for details). Three points are selected to represent typical locations of CPs for HSR, airport, and automobile (Figure 4.2). All the three CPs are located on the horizontal centerline of the synthesized urban areas for consistency. CPs for HSR, air, and auto are placed with straight-line distances to the mean center at approximately 1.7 km, 30 km, and 58 km, respectively.

Figure 4.2 Locations of the typical converging point for HSR, AIR, and AUTO.

Relationship between urban form and WAAT for HSR, AIR, and AUTO

Standard distances and WAAT of HSR, AIR and AUTO from the synthesized cities with different urban form compactness are calculated for the 12 synthesized cities (Table 4.1). Linear regression analysis then is applied to explore the relationship between the standard distances and WAATs of the different transport modes. The three fitted linear regression models, based on a total of 12 observations in accordance with the 12 scenarios, all have high R^2 values of 0.99. The

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high R^2 values indicate there may be some mathematical relationships between WAAT, which is calculated based on a constant travel speed across the synthesized city, and the standard distance of urban form. In real world scenarios, the R^2 values will be lower because of the variation introduced by varying speed limits at different levels of roads and the anisotropic property of travel speed (i.e., travel speed has different values when measured in different directions).

Table 4.1 Values of SD (in km) and WAAT of HSR, AIR, and AUTO (in min).

Scenario	SD (in km)	WAAT (in min)		
		HSR	AIR	AUTO
A	18.42	14.88	33.19	61.49
B	19.32	15.05	33.55	61.65
C	20.66	17.62	34.02	61.87
D	22.07	18.08	34.64	62.15
E	22.71	19.45	34.89	62.27
F	26.33	23.11	36.64	63.07
G	29.51	26.76	38.39	63.87
H	30.11	27.88	38.72	64.02
I	32.50	30.56	40.21	64.7
J	32.93	31.07	40.49	64.83
K	34.72	32.95	41.73	65.39
L	37.19	35.79	43.53	66.21

High positive relationships between WAAT and SDs for the three modes are identified and are expected as more dispersed urban forms tend to lead to a higher WAAT. Three regression lines representing the linear relationships are presented (Figure 4.3). The solid line represents the linear relationship between WAAT and SD for HSR, while the dashed line represents air, and the dotted line represents auto. Several key points can be drawn from the figure and the parameters of the three regression lines.
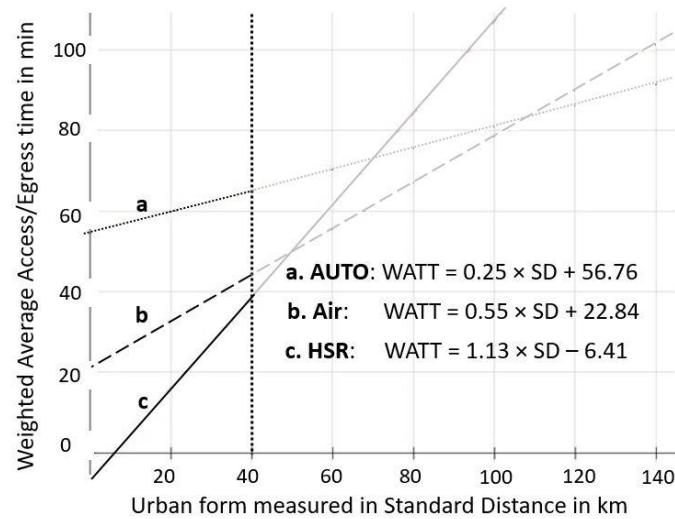
Figure 4.3 Regression lines between WAAT and SD for HSR, AIR, and AUTO.

1. For all three of the CPs, positive coefficients are found between WAAT and SD regardless of whether the CP is within UAs (i.e., HSR, air) or outside (i.e., auto). This indicates a more dispersed urban form will always lead to higher WAAT. In other words, the more compact the urban form is, the lower the overall WAAT will be regardless of the location of the CPs.

2. Coefficient indicates how dependent variable will respond to one unit change of the corresponding independent variable, i.e., how sensitive the dependent variable is to changes of the independent variables. When looking at the coefficients of the three lines, HSR has the highest coefficient, indicating that 1 km increase of SD will result in 1.13 min increase of WAAT. The WAAT increase for air under the same 1 km increase of SD is 0.55 min, and for auto it is 0.25 min. This indicates that the nearer the CP is to the city center, the more sensitive the WAAT of the corresponding mode is to changes of urban compactness. For HSR, the CP is the closest to city center and it is highly sensitive to urban compactness. As CPs move to city periphery and outside of the city (i.e., air and auto), WAAT becomes less sensitive to changes in urban compactness.

3. The vertical distance between the lines represents the differences of WAATs among the three modes at certain urban form compactness levels. As SD increases, the gaps among the

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three lines become smaller, indicating diminishing advantages of HSR over air and auto as cities become less compact. This suggests that more compact urban forms are preferred to fully take advantage of the centrally located HSR stations.

4. These numbers are derived from synthesized urban forms with 80×80 km in area. This confines the SD at around 40 km as the highest possible value (marked by the vertical dash line), which means that the three lines stop when SD reaches 40 km and will not intersect in reality. This indicates that while the advantages of centrally located facility by having shorter overall access time will gradually diminish as a city becomes less compact, in this simulation, however, the WATT of HSR will not surpass that of air, and the WATT of air will not surpass that of auto.

Overall, the results suggest that while a travel mode with a centrally located CP (i.e., HSR) has shorter overall access time, its advantage over travel modes with off-center CPs (i.e., air and auto) diminishes as the city becomes more dispersed. This is because the relatively high level of sensitivity to urban compactness of HSR as demonstrated by the higher coefficient value. Travel modes that have CPs at off-center locations, i.e., air and auto, on the other hand, tend to be less sensitive and are punished less by dispersed urban forms. This helps explain, from an accessibility perspective, the popularity of air and auto travel in the intercity travel market, as well as the obstacles HSR projects face in the United States where urban sprawl is common. For cities with dispersed population distribution, the results indicate the differences in WAAT for the three modes are relatively small. The small payback of the centrally located CP of HSR makes its establishment less justifiable. For cities with a compact urban form, e.g., European and Asian cities, on the other hand, the reward of a centrally located CP is high, leading to a greater incentive to build such modes for intercity travel.

The results from the above graph can also be interpreted as that certain transportation modes work best with certain types of urban form. For compact cities, modes with CPs close to city centers (i.e., HSR) are worthwhile as they significantly shorten overall access time; for

dispersed cities, on the other hand, modes with CPs that are farther away from city centers (i.e., air and auto) are more tolerable as the differences in overall access time are small when compared to centrally located CPs.

Relationship between gap and coefficient

If we use the term *gap* to refer to the spatial separation between a CP and city center and a gap value to describe the distance between them, a further phenomenon can be revealed from the findings reported in the previous section: the gap value plays a crucial role in determining the sensitivity of WAAT to varying urban forms. As shown in Table 4.2, when the gap value increases, the coefficient value decreases. While the three instances are indicative of the relationship, i.e., larger gap values lead to less sensitivity between access time and urban form, it will be more illustrative to expand the relationship from three discrete points to more points to reveal a detailed relationships on how sensitivity levels change with gap values.

Table 4.2 Comparison of coefficients with different gap values.

Assigned Mode	Gap (km)	Coefficient
HSR	1.7	1.13
Air	30	0.55
Auto	58	0.25

In addition to the above three pairs of data, coefficients for a total of 27 gap values, i.e., at 0.5 km, 2.5 km, 5 to 100 km at 5 km interval, are calculated and plotted for a more systematic exploration on the relationships between gap and the sensitivity (i.e., the coefficient) of overall access time to urban form (Figure 4.4). While coefficients always decrease as gap increase, the relationship is not always linear. From 0 to 40 km, a steeper decrease is observed; once the CP moves out of the city (40 to 100 km), the decrease rate slows down significantly and the curve flattens out.
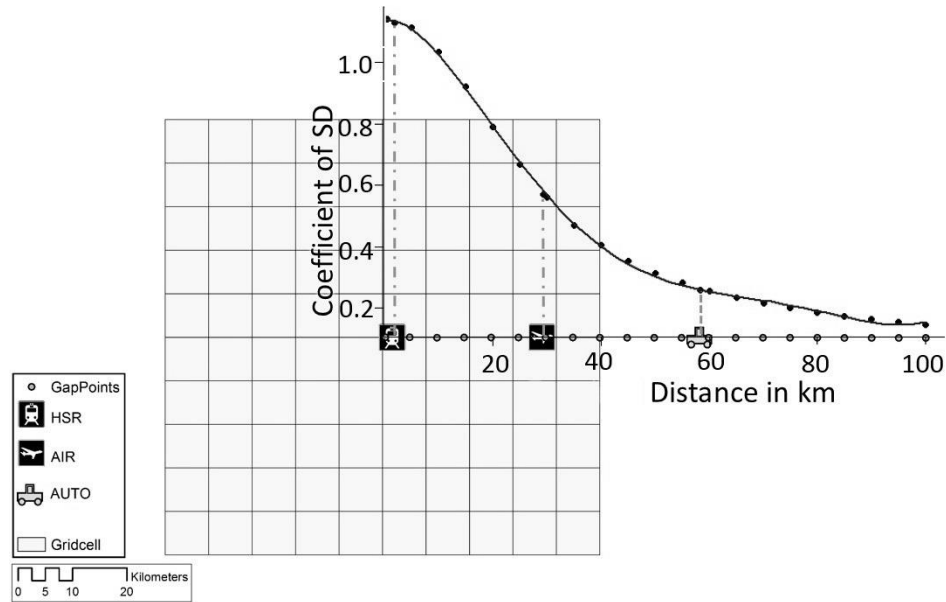
Figure 4.4 Relationship between gap and coefficient of WAAT and SD.

Based on the decreasing rate of the coefficient between WAAT and SD, a fast-changing

range (0-40 km) and a slow-changing range (40-100 km) can be identified from the curve. This

indicates WAAT's sensitivity to urban form decreases quickly when gap values increase within

the city, while the sensitivity declines at a slower rate once the CP moves out of the city. This

suggests that when CPs are inside the city, a more centrally located CP can yield higher

coefficient change, leading to higher access time reduction. Once out of the city, a closer distance

between CP and city center is not as impactful on reducing access time. Suppose we move the

CPs for both HSR and auto 10 km away from city center, i.e., gap values increase from 1.7 to

11.7 km for HSR, and 58 to 68 km for auto, their impacts on the relationships between WAAT

and SD can be demonstrated (Figure 4.5). It is obvious that the 10 km increase in gap value has a

higher impact on the coefficient for the case of HSR (from 1.13 to 0.96), while little impact on

auto (from 0.25 to 0.21). If the above section demonstrates a compact urban form is preferred for

centrally located CPs by leading to reduced access time, this section illustrates the reduction of

access time is more significant when CPs are moving inside the city; once CPs move out of the

city, the level of urban form's compactness will have less impact on access time. This suggests

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that for travel modes with CPs outside of the city (i.e., auto), their resilience to sprawling urban forms will be higher, explaining from an accessibility approach why intercity auto travel is popular among sprawled U.S. cities.
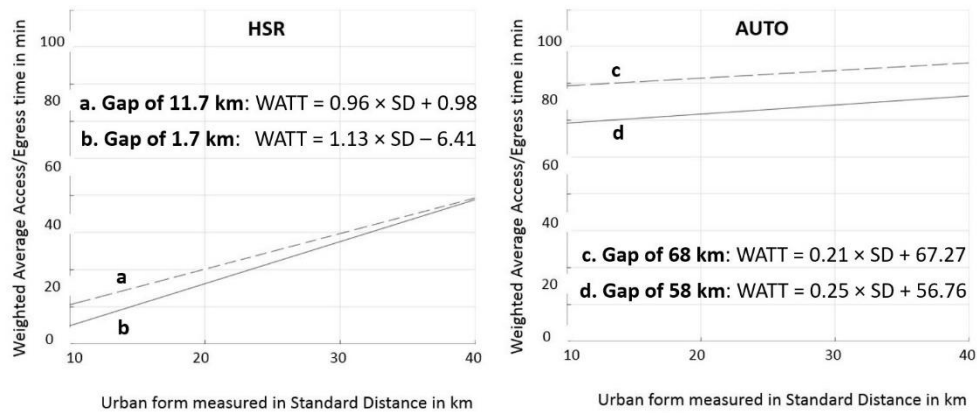
Figure 4.5 Changes of sensitivity between WAAT and SD with a 10-km increase in gap value.

Implications on HSR development in the United States

Like many other forms of transport infrastructure, the accessibility impact of HSR is one of the main channels to boost a city's economic performance by bringing resources and opportunities closer. A new HSR system offers intercity passenger travel and is expected to increase accessibility with reduced travel time. This reduced travel time is not only attributed to the high-speed during the on-board portion of the trip but to an often centrally located facilities leading to shorter access time. The latter benefit of the HSR, however, is dependent on the urban form of the cities it serves. Through a simulation approach, this study identifies a high correlation between overall access time and urban form compactness. To fully take advantage of a HSR system's often centrally located traveling facilities, a concentrated distribution of potential passengers at city center is preferred. Sprawling urban forms, on the other hand, will lead to significant increase in access time for centrally located facilities (i.e., HSR stations) and negate the station-wide accessibility advantage of HSR. Relating to the dispersed urban form of U.S. cities, this finding explains from an accessibility perspective the difficulty of introducing HSR to

U.S. cities due to their often sprawling urban form. It also explains that automobile and airport intercity travel are popular due to their relatively high resilience to such urban forms.

This further confirms that HSR development needs to be undertaken as a package – to fully reap the accessibility advantage at the intracity level, a HSR project should come with strategic plans that involve stimulating economic development of its surrounding areas to foster high-density development. This makes HSR a natural fit to lead and complement urban planning strategies such as smart growth, downtown revitalization, transit-oriented development, etc. that advocate for high-density and mixed-use development. On the one hand, a HSR station can function as a focal point of activities and foster a more cohesive development pattern, assisting the planning goals of the above strategies. On the other hand, these planning strategies – through promotion of high density and mixed-use urban development – can in turn help boost the potential accessibility advantages of HSR against air and auto at the intracity level and justify the needs of HSR systems.

While this chapter presents a comprehensive analysis on how access time is related to varying urban forms, it is worth noting that access time constitutes only a portion of intercity travel under the door-to-door framework. Ultimately, the benefits of shorter access time need to be incorporated as an integral part of the door-to-door framework when depicting HSR's accessibility impact over air and auto travel. Also, due to the nature of the study, this chapter builds the analysis based on data derived from synthesized cities. In reality, a city may take a very complex form and urban form's impact on access time could vary between cities. A case study based on actual American cities will complement the theoretical analysis and offer a venue to validate the effectiveness and usefulness of the proposed door-to-door framework.

CHAPTER V

AN ACCESSIBILITY STUDY ON THE PROPOSED DALLAS-HOUSTON HSR CORRIDOR:

AN EVALUATION OF MODAL COMPETITION BASED ON THE DOOR-TO-DOOR

TRAVEL TIME FRAMEWORK

The previous chapter provides a theoretical analysis based on synthesized cities and focuses on the impact of city compactness on the *overall* access time of the entire city. However, due to the complexity of a city's spatial form, access time to a traveling facility could *vary* significantly across the city. To reveal the spatial variation of HSR accessibility within a city, this chapter applies the door-to-door travel time approach at the census block group level in the proposed Dallas-Houston HSR corridor. By calculating and incorporating the varying access and egress times from HSR and its competitors, i.e., air and auto, this chapter reveals detailed spatial patterns of accessibility advantages of HSR when considering modal competition at the sub-city level. Results of this chapter can help HSR planners better understand the competitions faced by HSR from other existing travel modes and assist HSR planning at the local and regional levels.

Existing methods for intracity accessibility analysis and its drawback

Intracity accessibility analysis, or station-wide accessibility analysis, of a public transport facility aims to determine the areas it serves and often involves delineation of the catchment area of its traveling facility. Catchment area generally refers to the geographic area within which most travelers are comfortable using the service (Flamm and Rivasplata 2014; Martínez et al. 2016). When determining catchment areas of certain traveling facilities, traditional approaches often rely

on defining certain distance or travel time thresholds around the traveling facilities. These approaches usually involve defining a circular buffer based on certain Euclidean distance or an area that can be reached within certain time via transport network around a station (Gutiérrez, Cardozo, and García-Palomares 2011). Different standards have been used to determine the catchment areas for HSR stations. Some studies argue that the catchment area of an HSR station is similar to that of a transit station, which usually serves up to 5 km (Alshalalfah and Shalaby 2007; Catz and Christian 2010; Murakami and Cervero 2010). Other studies contend that as intercity travel terminals, HSR stations should be given a much larger catchment area, which can serve up to 25 km (Leinbach 2004; Todorovich and Hagler 2011; Martínez et al. 2016). Because of the huge differences in deciding the catchment area of an HSR station, it is quite common for researchers to perform multiple sets of analyses with different standards of HSR station catchment areas in their HSR station accessibility studies. These threshold values are largely subjective to researchers and there usually is no clear support for why a specific value of distance or travel time is chosen. For example, Zhong, Bel, and Warner (2014) did a comparison study between the proposed Los Angeles-San Francisco HSR route in California and the Madrid-Barcelona HSR route in Spain. A set of catchment areas at 5, 10, and 25 km was selected and applied in their study.

One drawback of using service area when depicting catchment area for intercity travel is that it only considers one end of an intercity trip. An intercity trip, however, happens at multiple levels and have more than one segment. A short access trip in the origin city does not guarantee overall short travel time, since the overall time is determined also by segments including on-board travel time and egress travel time at the destination city. The traditional service area method also does not factor in modal competition when multiple choices are presented and are competing. When multiple transportation modes exist, it is reasonable to assume that travelers will consider all possible choices and choose the most cost-efficient mode. Competing modes

thus have to be taken into consideration when delineating catchment areas of any intercity

traveling facilities.

Using the door-to-door framework that is proposed in Chapter III, this section introduces

a new method to delineate catchment areas for intercity travel that 1) incorporates all major

segments of intercity trips, and 2) considers modal competition from an accessibility perspective.

The method is then applied to the proposed Dallas-Houston HSR project to reveal the spatial

variation of the accessibility advantages of HSR at the sub-city level. The results are expected to

help researchers and transportation planning authorities gain better understanding of how a

proposed HSR service affects intercity travel and competes with other transportation modes.

Study area and multimodal network setup

a. Study area

The Dallas-Houston HSR project is proposed by Texas Central Railway (TCR), which is

a private entity that aims to build the HSR route using primarily private money. The Texas

Department of Transportation (Texas DOT) estimates the cost of track construction at $10 billion

(Texas DOT 2017a). The HSR route will connect the 6th (Dallas-Fort Worth-Arlington) and 7th

(Houston-The Woodlands-Sugar Land) most populous urbanized areas in the country in under 90

minutes with maximum speed of 330 kilometers per hour (Texas Central 2016). Being at the

initial stage of HSR network development, the Dallas-Houston HSR resembles a corridor pattern

as opposed to the more complicated hub-and-spoke system.

An overview map of the proposed Dallas-Houston HSR map (Figure 5.1) shows the

geographic setting of the route as well as existing major transportation hubs in the corridor. The

HSR route information is obtained from the TCR website and resembles the utility alignment

plan. The locations of the two proposed HSR stations in Dallas and Houston are also based on the

information provided in the TCR website. Urbanized areas of Dallas-Fort Worth-Arlington

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(DFWA) and Houston are highlighted in red and define the geographic boundary of the two urban areas in this study.

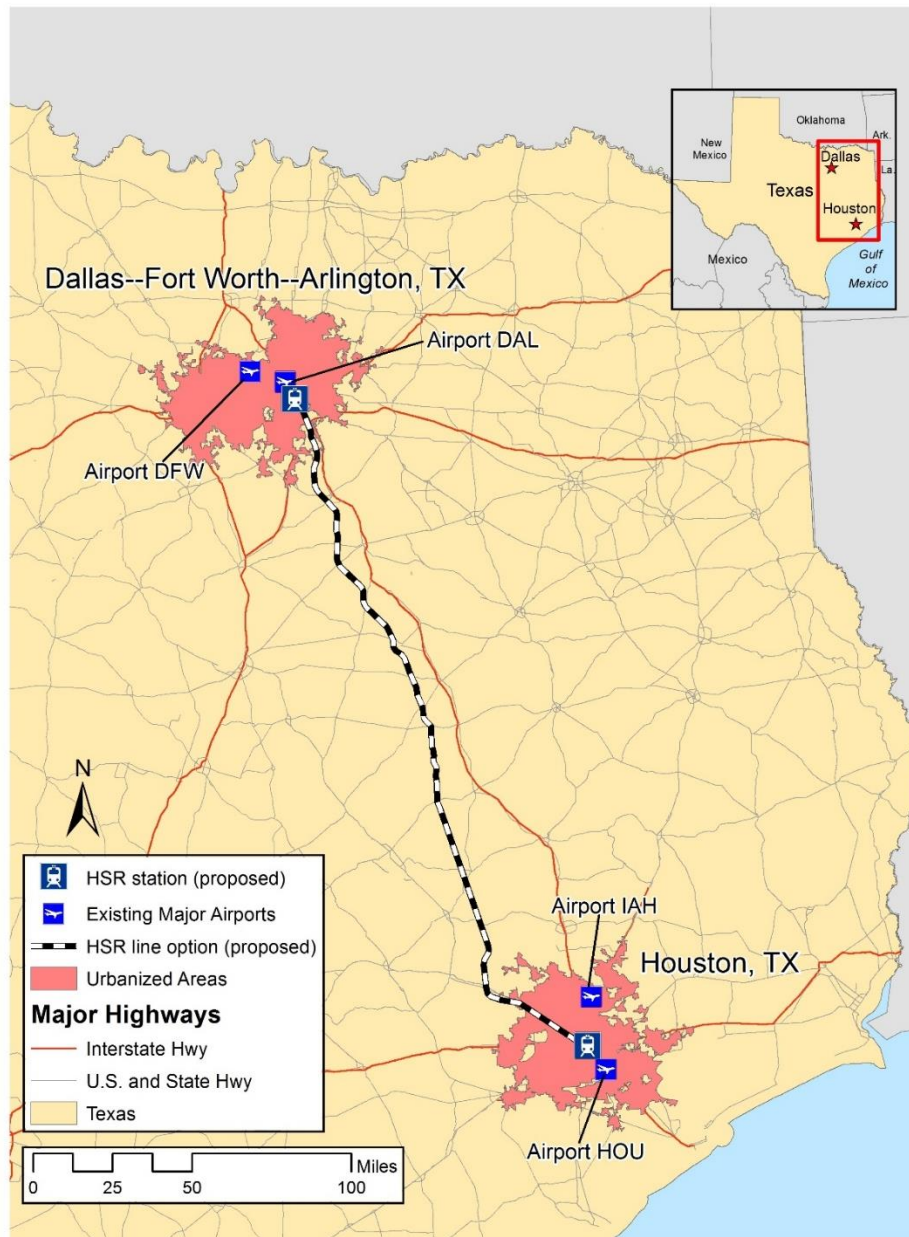Figure 5.1 Overview map of proposed HSR line between Dallas and Houston.

Including the proposed HSR, there will be a total of four major choices for a person to travel between the Dallas and Houston area: Interstate 45 serves as the major connector by road between the two major Texas cities, while airline routes exist between two separate pairs of airports – Dallas Love Field (DAL) to William P. Hobby (HOU) and Dallas/Fort Worth

International (DFW) to George Bush Intercontinental (IAH). For simplicity purposes, I will use the International Air Transport Association's (IATA) Location Identifier, the unique 3-letter code included in the parentheses, to refer to the above airports throughout this research. In terms of the air traffic volumes between the two cities, the 2017 traffic volume data show a majority of air travels are from Airports DAL to HOU and from Airports DFW to IAH, which account for 45.2% and 44.5% of the total traffic, respectively (Bureau of Transportation Statistics 2018). While air travels from Airports DFW to HOU exist, they only account for 10.3% of the total air traffic volume between Dallas and Houston and are not considered in this study.

Airports DAL and HOU were constructed at an early time and are located at the then-outskirts of the cities in the 1910s and 1920s, respectively. As the cities expanded, the two airports became surrounded by subsequent developments. Comparing to Airports DFW and IAH that were built at later years, Airports DAL and HOU are located relatively close to city downtowns. The relatively close-to-downtown locations of Airports DAL and HOU can make air travel between those two airports a potentially strong competitor with the proposed HSR service.

The proposed HSR will inevitably compete with the existing travel choices via air and auto. For simplicity purposes, this research uses HSR to denote the mode of HSR travel between the two cities, AIRDH to denote air travel between Airports DAL and HOU, AIRDI to denote air travel between Airports DFW and IAH, and AUTO to denote automobile travel in the following sections.

b. Multimodal network setup

Based on the proposed door-to-door framework in Chapter III, a multi-modal network consisting of four intercity travel modes is constructed. This study uses all census block groups in the DFWA and Houston urbanized areas. A total of 3474 block groups in DFWA and 2502 block groups in Houston are included in this study. Time cost at each segment in the door-to-door framework is gathered from multiple sources and displayed below (Table 5.1). At the intercity

level, timetable-based travel time is obtained to represent travel time. At the intracity level (i.e., access time and egress time), access and egress times from each census block group to each traveling facility are calculated with automobile travel as the means to complete the travel. The adoption of automobile travel as access and egress mode in Dallas and Houston is due to the heavy auto dependency of the two cities. Road network data are acquired from the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) data set (U.S. Census Bureau 2017). Network-based travel time is derived from free-flow travel speed, while speed limit information is obtained from the Texas DOT road inventory data set (Texas DOT 2017b). Waiting time is estimated by the time a traveler is required to arrive at the traveling facility before departure time. For example, most airlines require passengers to arrive at least 60 minutes prior to departure for domestic flights, while high-speed rail services usually require riders to arrive 30 minutes in advance at train stations. On-board travel time is obtained from the timetables of corresponding services. While largely dependent on intermodal connectivity at the specific traveling facility, transfer time is difficult to acquire and gather, and in this study it is estimated by the physical sizes and passenger volumes of the traveling facilities.

Table 5.1 Major segments of different intercity travel modes between DFWA and Houston at the block group level.

Scenario	Access/ Egress	Waiting Time	On-board Travel time	Transfer time	Egress	Total travel time
HSR	Depends	30[*]	90	20[†]	Depends	Sum of each part
AIRDH	Depends	60[*]	60	20[†]	Depends	Sum of each part
AIRDI	Depends	60[*]	70	25[†]	Depends	Sum of each part
AUTO	0	0	Depends	0	0	Sum of each part

[*] Time estimated based on traveling facility recommendation and timetable

[†] Time estimated based on physical sizes and passenger volumes of facilities

c. **Catchment area delineation based on door-to-door framework**

Existing studies have frequently used the concept of service area to delineate the catchment area of a traveling facility. A service area depicts how many potential customers are

within reach at certain thresholds. The reasoning behind the selection of the threshold, however,

is usually ambiguous and subjective to researchers, and there is no widely accepted method to

determine the size and shape of the catchment area of HSR service (Martínez et al. 2016).

Moreover, current common practices of determining catchment areas of intercity traveling

facilities focus only on one end of the trip, and do not consider the impact of competing modes in

the process.

To tackle the above drawbacks, a city pair based catchment area delineation method is

developed that considers all segments of an intercity trip and incorporates modal competition

between a pair of cities. The core idea is to determine the shares of the optimal modes from one

subunit of a city to all subunits in the other city, where the optimal mode is determined based on a

door-to-door approach. First, a multimodal network is built to calculate door-to-door travel time

between all subunits in a pair of cities. Let A_i represents subunit i (i = 1,2,3, …, m) in city A, let

B_j (j = 1,2,3, …, n) represents subunit j in city B. Let α, β, γ… k denote existing travel modes

between city A and B. Origin-destination (OD) matrices with $m \times n$ dimension can be calculated

for each travel mode based on door-to-door travel time (αAB, βAB, γAB, …, kAB). The fastest

mode for each OD pair from A_i and B_j can be determined by finding the minimum values from

[αAB, βAB, γAB, …, kAB]. An advantage mode matrix AdvMAB of $m \times n$ can then be derived

with each cell represents the fastest mode. The AdvMAB therefore contains the information of

the fastest mode (i.e., α, β, γ,…, k) to complete the trip between each OD pair of A_i and B_j. Each

row of the matrix represent a list of the fastest modes from A_i to all subunits in city B, while each

column represent a list of fastest modes to B_j from all subunit in city A. This AdvMAB can

demonstrate how frequently a particular mode shows up between the two cities at the subunit

level.

Based on the AdvMAB matrix, the catchment area of each mode can be delineated at the

subunit level. The share of each mode at the subunit level can be calculated by summing up rows

and columns. For example, for A_i, mode α is the fastest mode to 30% of all subunits in B, mode β is the fastest mode to 50% of all subunits in B, etc. The share of a particular mode will likely to decrease for subunits that are located farther away from its traveling facility due to increasing access and egress times. By mapping out the spatial distribution of the share of a mode, its catchment area – which centers on its traveling facility and diminishes across the city – can be delineated.

Results and discussions

a. Modal advantage at the census block group level

A 3474×2502 matrix is derived with each cell storing the fastest mode between the census block groups in DFWA and Houston. To highlight changes of mode advantage pattern in accordance with a block group's distance to city centers, the rows (block groups in DFWA) and columns (block groups in Houston) are sorted by the straight-line distance of block groups to downtowns (i.e., the geographic centers of the Dallas and Houston central business districts). The sorted matrix is then converted into a raster image with the same dimension for presentation (Figure 5.2). Each color in the raster stands for a particular mode: red represents HSR, green represents AIRDH, and blue represents AIRDI.

Several conclusions can be drawn based on the rasterized modal advantage matrix. Firstly, AUTO does not show up in the whole matrix, suggesting it is not the dominant travel model from a door-to-door perspective when travel time is the only determining factor. In reality, however, travel time is only one of the many factors that affect a traveler's choice. Because of the high level of comfort and privacy it offers, as well as its ability to deliver door-to-door service without the hassle to make intermodal connections, auto travel remains a popular intercity travel mode albeit the relatively high cost in travel time. A detailed travel choice model that considers all the above aspects will be needed to determine the actual competitiveness of automobile travel.

While an extended discussion on carrying out such a modeling analysis is beyond the scope of this research, the detailed door-to-door travel time generated in this study can serve as a more
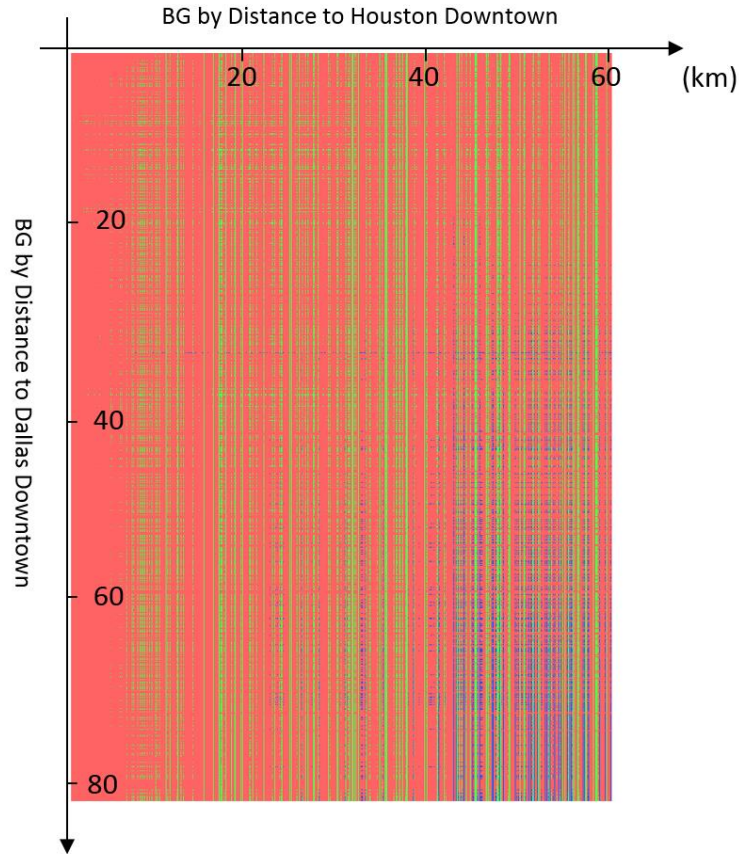
Figure 5.2 Raster representation of modal advantage at the census block group level.

accurate travel time estimation parameter for the modeling approach. Secondly, more continuous lines from block groups in Houston (vertical lines) are observed than that from block groups in DFWA. This indicates modal advantage tend to be more monopolistic for individual block groups in Houston – the same mode of transportation will be the fastest choice regardless of the location of the destination in DFWA. For block groups in DFWA, however, more interrupted horizontal lines signify the fastest mode for the same block group in DFWA varies based on the destination location in Houston. Finally, some spatial patterns can be examined from the matrix. Because of the close location of HSR stations to the downtown areas, HSR will be the fastest mode for trips

that start and end within approximately 5 km of both downtowns. AIRDI starts to show up as a competitive travel mode only for block groups with distances of 35 km or more to downtowns.

The rasterized matrix offers a simplified representation of modal advantages at the block group level and reveals limited spatial patterns. Based on the rasterized matrix, the next section incorporates the locational information of each block group and depicts catchment areas that will illustrate the spatial patterns of modal advantage of each mode in the two urbanized areas.

b. Catchment area delineation

Based on the modal advantage matrix, shares of modal advantage for each of block group are calculated and catchment area maps of major intercity traveling facilities are produced for the DFWA and Houston region. A red, green, blue (RGB) color mix is also applied for efficient representations of the catchment areas for HSR, AIRDH, and AIRDI. To achieve this, the shares of the above three modes for each block group were scaled to 0-255 and assigned to one of the three colors. The share of HSR is assigned to red, AIRDH to green, and AIRDI to blue. As demonstrated in the symbology graph (Figure 5.3), different compositions of RGB values result in different colors – a color's RGB composition is in reverse proportion of its distance to the pure RGB colors located at the middle point of each side of the triangle. A color with the specific RGB composition is then set to be the fill color of that particular block group. For example, Magenta have the same distance to Red and Blue, and are at the farthest possible position from green. Thus a block group in Magenta color will indicate it has a half-half share of HSR and AIRDI, and no share of AIRDH. The gradual change of color across the block groups, resulted from changes of the RGB code, will not only demonstrate where the catchment area of each mode is located, but also show the transitions of catchment areas among different modes.
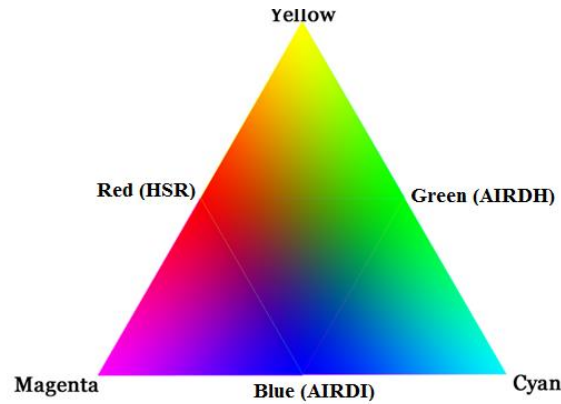
Figure 5.3 Symbology showing RGB color mixing. Image modified from Briggs (2007).

Different from traditional catchment maps, the new catchment area maps of major intercity traveling facilities in DFWA (Figure 5.4) and Houston (Figure 5.5) are based on the method that uses the door-to-door approach and accounts for modal competition. When looking at the maps, the catchment areas of HSR – represented by red – are the most prevalent for both cities. For example, HSR is the dominant mode at both location A in DFWA (color code: Red 245, Green 10, Blue 0) and location D in Houston (color code: Red 255, Green 0, Blue 0). This can be attributed to the relatively central location of HSR stations in the two UAs, resulting in overall shorter access and egress times at both ends of the trip. AIRDH and AIRDI, due to their relatively off-center locations, claim their own portions of territory and compete with HSR more heavily as distances to downtowns increase.

The effect of adopting the door-to-door approach can be best illustrated by the catchment area map in DFWA. From the DFWA map, it is clear that HSR has a disproportionally large dominance over the whole region, while Airports DAL and DFW are not able to establish their dominance even around block groups that are close to them. For example, for block groups that are relatively close to Airport DAL at location B (color code: Red 158, Green 97, Blue 0) and Airport DFW at location C (color code: Red 164, Green 62, Blue 29), HSR remains to be the favored travel mode to a majority of block groups in Houston. The main reason for the overwhelming dominance of HSR is because what happens at the other end of the trip – the

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Figure 5.4 Catchment area map of traveling facilities in DFWA.

Figure 5.5 Catchment area map of traveling facilities in Houston.

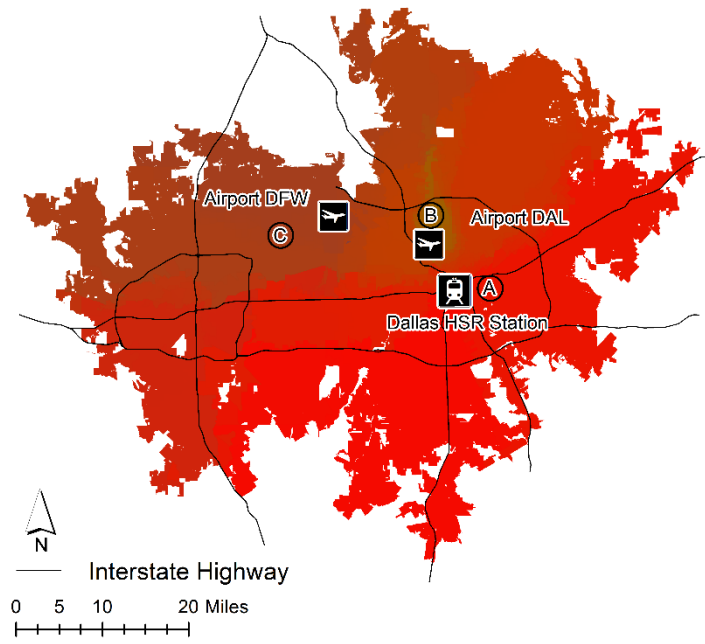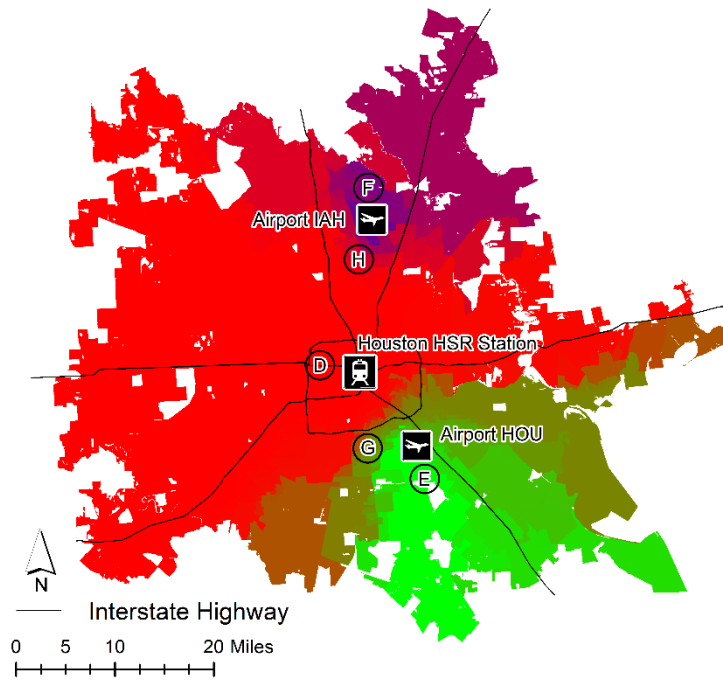relatively off-center locations of Airport HOU and Airport IAH in Houston weaken the competitiveness of the two modes even in the DFWA region.

For Houston, on the other hand, the three traveling facilities are far apart enough to claim their own territory. The locations of their corresponding facilities in DFWA are also relatively clustered, making the average travel time at the other end not significantly different. For example, Airport HOU has absolute dominance at location E (color code: Red 0, Green 255, Blue 0) as demonstrated by the green color; Airport IAH has a considerable share at location F (color code: Red 109, Green 0, Blue 146). Transition zones can also be identified between different modes as suggested by the mixtures of different colors at location G (color code: Red 123, Green 132, Blue 0) and location H (color code: Red 165, Green 0, Blue 90). For block groups in the transition zones, the optimal mode will depend on the location of the destination in DFWA.

The two catchment maps also correspond to the rasterized mode advantage matrix presented in the previous section. For DFWA, there are less pure red, green, or blue colors – even the red color around the HSR station in DFWA is a mix of red and green. The mode advantage raster corresponds to this by having few complete horizontal lines, indicating a mixture of optimal modes for block groups in DFWA. For Houston, on the other hand, there are more pure colors, suggesting block groups in Houston are more likely to have one single dominant mode regardless of the locations of the destinations in DFWA.

In summary, this approach provides a more theoretically sound method when depicting catchment areas of particular intercity travel modes. Compared to the traditional service area approach, this method considers all major segments of intercity trips by adopting a door-to-door approach, and it also factors in modal competition by including existing intercity travel modes. The RGB color mix also offers a straightforward way to demonstrate spatial patterns of the catchment areas for the three traveling facilities.

Summary

This chapter demonstrates how the proposed door-to-door approach can be applied to improve accessibility analysis of intercity travel. By integrating both the intra- and inter-city segments, the door-to-door approach is able to capture a more complete picture of intercity travel and reveal the spatial variations of accessibility patterns across the city. Based on the door-to-door framework, a new method to depict catchment areas for intercity traveling facilities is developed. Compared to the traditional service area approach, this new approach offers better theoretical support by considering all major segments of intercity trips, as well as the capability of factoring in modal competition.

The Dallas-Houston HSR case study demonstrates how this method can help analyze the station-wide accessibility of HSR in the face of competition from existing intercity travel modes at the sub-city level. The relatively central locations of the proposed HSR stations in both the DFWA and Houston regions give HSR an edge when competing with existing air and auto travel. Under the door-to-door framework, locations of corresponding traveling facilities in one city also have an impact on the catchment area at the other city. When HSR stations are both located close to downtowns as is the case in the proposed Dallas-Houston HSR project, the combined shorter travel time in access and egress trips greatly increases the competitiveness of HSR from an accessibility perspective.

With multiple HSR proposed in the United States and the construction of a state-wide HSR system started in 2015 in California, there is no denying that HSR is getting more attention in the United States. Based on the door-to-door framework, this chapter provides an innovative way to depict the spatial patterns of accessibility advantages of HSR at the sub-city level under the competition of existing travel modes. The results can help policy makers and transportation planners gain better understanding on the competitiveness of HSR services and make informed decisions on HSR development.

CHAPTER VI

URBAN FORM DEVELOPMENT TREND IN THE DALLAS-HOUSTON CORRIDOR AND

ITS IMPLICATIONS ON HSR DEVELOPMENT

Previous chapters have demonstrated that urban form has a direct impact on the overall

accessibility advantages of HSR over its competitors such as air and auto by affecting access and

egress times. Urban form, under the definition that refers to the spatial shape, size, and

configuration of settlement, is intrinsically a dynamic phenomenon and constantly evolving. This

chapter contributes to the study of HSR accessibility by focusing on the analysis of urban form

development *trend* in the Dallas and Houston areas and its implications on HSR development in

the region. With the help of historic Longitudinal Employer-Household Dynamics (LEHD) data

sets from 2002 to 2014 (U.S. Census Bureau 2015), areas with significant changes of

employment and population in both cities are identified and the related implications on HSR

development are discussed. Special emphases are placed on the investigation of 1) the distinct

spatial employment and population distributions in both DFWA and Houston, 2) changes of the

spatial distribution, and 3) their impacts on the overall access/egress time to the proposed HSR

and existing air transportation.

The LEHD data sets are used to reveal the spatial distributions of employment and

population in both DFWA and Houston. Based on multiple administrative sources, including

unemployment insurance earnings data and the quarterly census of employment and wages data,

the LEHD data set reports counts based on a person's place of work (employment count) and

location of residence (population count) (Graham, Kutzbach, and McKenzie 2014). Due to the

nature of the data sources, the LEHD data only include the employed population, i.e., persons who have a job that offers positive earnings. The LEHD data set provides spatially fine-grained data by reporting data at the census block level. Because of the high spatial resolution, the LEHD data are widely used to study urban employment-resident mismatch and commute pattern analysis at intracity levels. This study aggregates the LEHD data to the census block group level as the unit of study to reduce computation intensity while retaining its ability to demonstrate detailed geographical patterns. The LEHD data are available yearly from 2002 to 2014, which confines the temporal dimension of this study.

Employment and population distributions represent the distributions of potential passengers from two different types of trips, namely business trips and leisure trips. Based on trip origin and destination, business trips are defined as trips with origins and destinations in employment sites, while leisure trips have their origins and destinations in residential sites. By this definition, the spatial distribution of employment will have a direct impact on business trips, and the spatial distribution of population have a direct impact on leisure trips. By examining the spatial distributions of both, this research can demonstrate how the temporal trends impact both business trips and leisure trips.

Standard distance (SD), which was introduced in Chapter III, remains to serve as an overview measurement of the spatial distributions of employment and population. Getis-Ord Gi* hot spot analysis (Getis and Ord 1992) is used to locate spatial clusters of extreme values of employment and population in DFWA and Houston. By mapping out the hot spot clusters, this research demonstrates and compares the spatial distribution of clusters of extreme values based on employment and population in DFWA and Houston. The 13-year period of data from 2002 to 2014 also allow a study on the temporal changes of the spatial distributions of employment and population in the two urban areas.

Results and discussions

a. Overall change of employment and population from 2002 to 2014

Total counts of employment and population in general see gradual increases from 2002 to 2014 (Figure 6.1a, 6.1b). The total numbers of both employment and population in Dallas and Houston witness steady increases of around 70,000 per year on average, except during the aftermaths of the recession in early 2000s and the 2007-2008 financial crisis. Total population counts within the urbanized areas are slightly lower than employment counts, likely indicating possible commuters living outside of the urbanized areas but who work inside the areas.
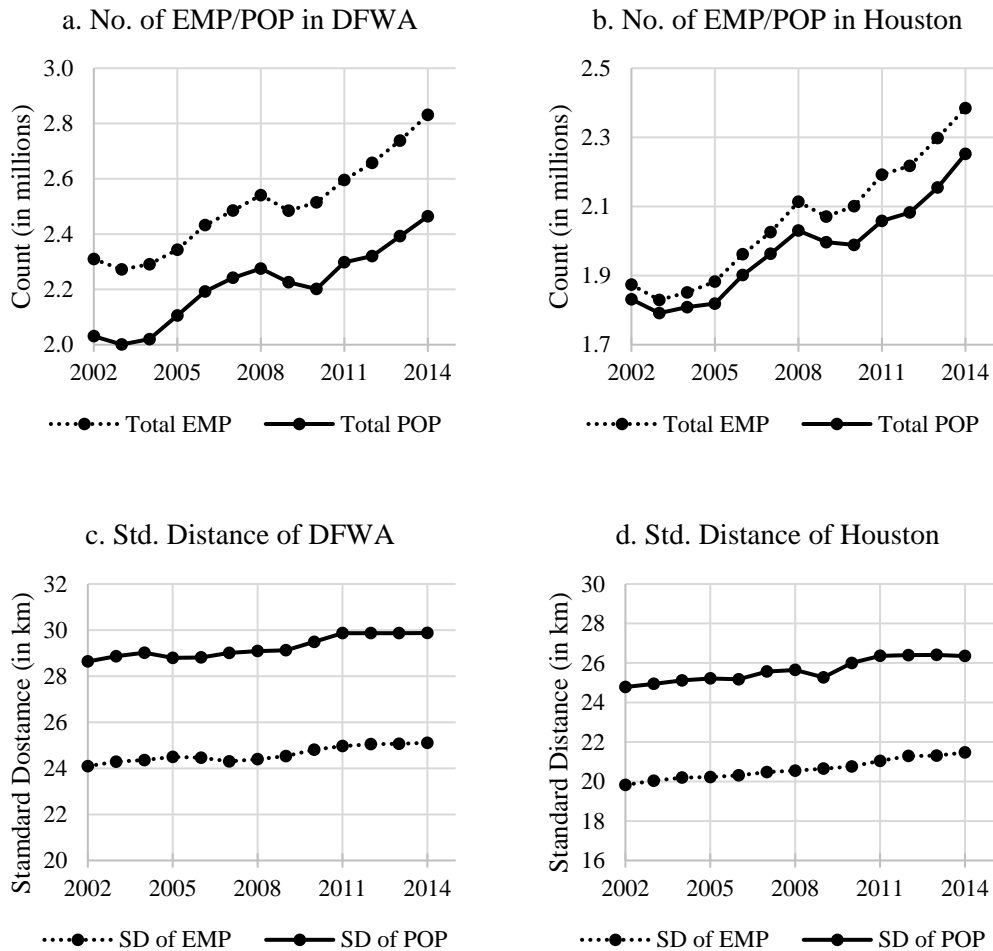

Figure 6.1 Trends of number of total employment and population changes (a and b) and standard distance changes (c and d) for DFWA and Houston from 2002 to 2014.

The SDs of employment and population in Dallas and Houston show a gradual increase from 2002 to 2014 (Figure 6.1c, 6.1d). The SDs of population are larger than that of employment, indicating a spatial distribution difference in which population distribution is usually more spread out than that of employment. Since SD will remain the same if growth happens evenly across the whole urbanized area, the increases in SDs indicate uneven spatial development patterns, i.e., more growth at off mean center locations for both employment and population from 2002 to 2014 in the two urbanized areas.

b. Spatial distribution of employment and population

To explore the spatial patterns of population and employment distributions, hot spot analyses on employment and population are carried out at the census block group level to reveal spatial clusters of extreme values in DFWA and Houston (Figure 6.2). For the DFWA area, clusters of high employment can be identified at the Dallas downtown area, Fort Worth downtown area, the I-35E/I-635 corridor northwest of the Dallas downtown, and northern Dallas. Clusters of high population values, on the other hand, are commonly observed at the peripheries of the area. For Houston, the maps also demonstrate similar patterns showing the dichotomy with employment concentrated at city centers and population at city peripheries, confirming the gaps that are found in standard distances between employment and population in the above section.

Major intercity traveling facilities (i.e., proposed HSR stations, airports) are located at different parts of the urbanized areas due to historical and strategic reasons (Figure 6.2). The proposed HSR sites in both cities are located in close proximity to the traditional downtowns to provide direct city-center to city-center connections. In terms of geographic proximity to city centers, the airports in Dallas and Houston can be divided into two distinctive groups: Love Field in Dallas and Hobby in Houston were built in the early stages and are located relatively close to city centers, while DFW and IAH were built later and located in the peripheries of the urban areas.

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a. Employment of DFWA

b. Population of DFWA

Low-low cluster
High-high cluster
Existing Major Airport
HSR Station (proposed)
Interstate Hwy
Urban Area

*Cluster significant at 90% confident level

c. Employment of Houston

d. Poppulation of Houston
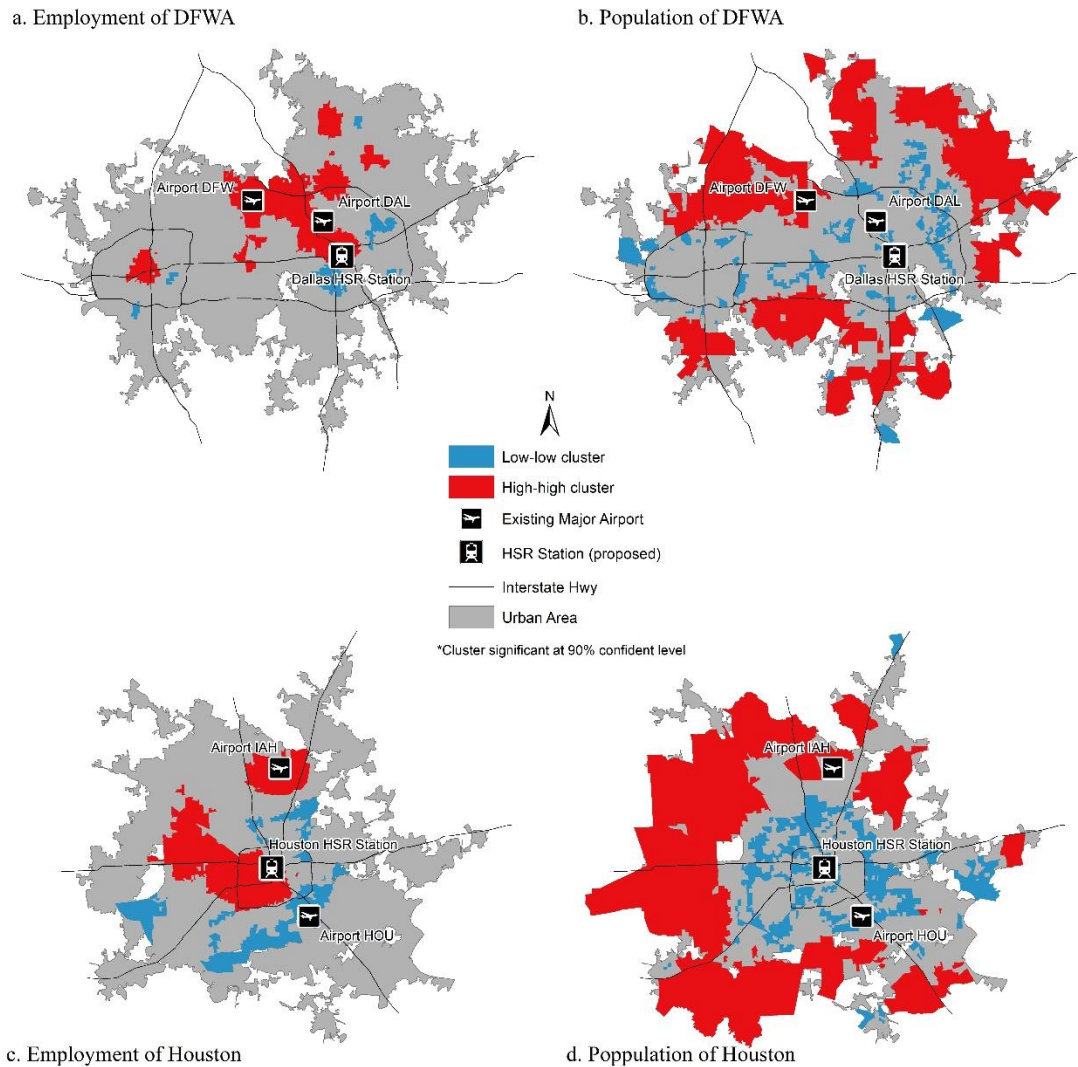
Figure 6.2 Hot spot maps of employment and population in DFWA and Houston in relation to the proposed HSR stations and major airports in 2014.

The relative locations of different intercity traveling facilities, as well as the spatial mismatch of employment and population distributions, makes accessibilities to different travel modes vary for passengers involved in different types of trip. The proposed HSR stations in both DFWA and Houston will provide great accessibility to employment sites at city centers. Because of urban sprawl, however, employment sites also spread out across the urban areas and are not concentrated in the traditional downtown areas only. For example, the percentages of

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employment located at downtown areas only account for 4.05% and 4.61% of the total

employment of DFWA and Houston, respectively (see Table 6.1 for details). In terms of

population, the spatial distribution of population shows the majority of population is located at

the peripheries of the urbanized areas, resulting in a larger overall distance to the proposed HSR

stations than that from the employment sites. This indicates while the proposed HSR will bring

considerable time savings for city center to city center trips, the advantage of HSR stations over

airports may not be as high for a majority of both business and leisure trips that start or end at

outlying employment sites and/or population sites.

c. Employment and population change between 2002 and 2014

With 2002 as the base year, employment and population changes between 2002 and 2014

are calculated at the census block group level. Hot spot analyses are then carried out based on the

value of change for both employment and population, respectively. The hot spot maps of

employment and population change between 2002 and 2014 (Figure 6.3) show that *growth* in

both employment and population happen more often at off center locations. Increases in

employment in DFWA are generally observed at the northern part of the urbanized area (Figure

6.3a). For Houston, the 2014 employment increased mostly at the northwest of Houston (Figure

6.3c). For both cities, most of the clusters of high increases in employment from 2002 to 2014

happened in areas relatively far away from the traditional downtowns where the proposed HSR

stations will be located at. For population, high increases happened even more predominantly at

the peripheries of the two urbanized areas (Figure 6.3 b and d). Hot spot maps are also generated

based on annual employment and population changes from 2003 to 2014 using 2002 as the base

year. The series of growth maps from 2003 to 2104 show similar patterns.

a. Employment Change of DFWA　　　　　　　b. Population Change of DFWA

Low-low cluster
High-high cluster
Existing Major Airport
HSR Station (proposed)
Interstate Hwy
Urban Area

*Cluster significant at 90% confident level

c. Employment Change of Houston　　　　　　d. Poppulation Change of Houston
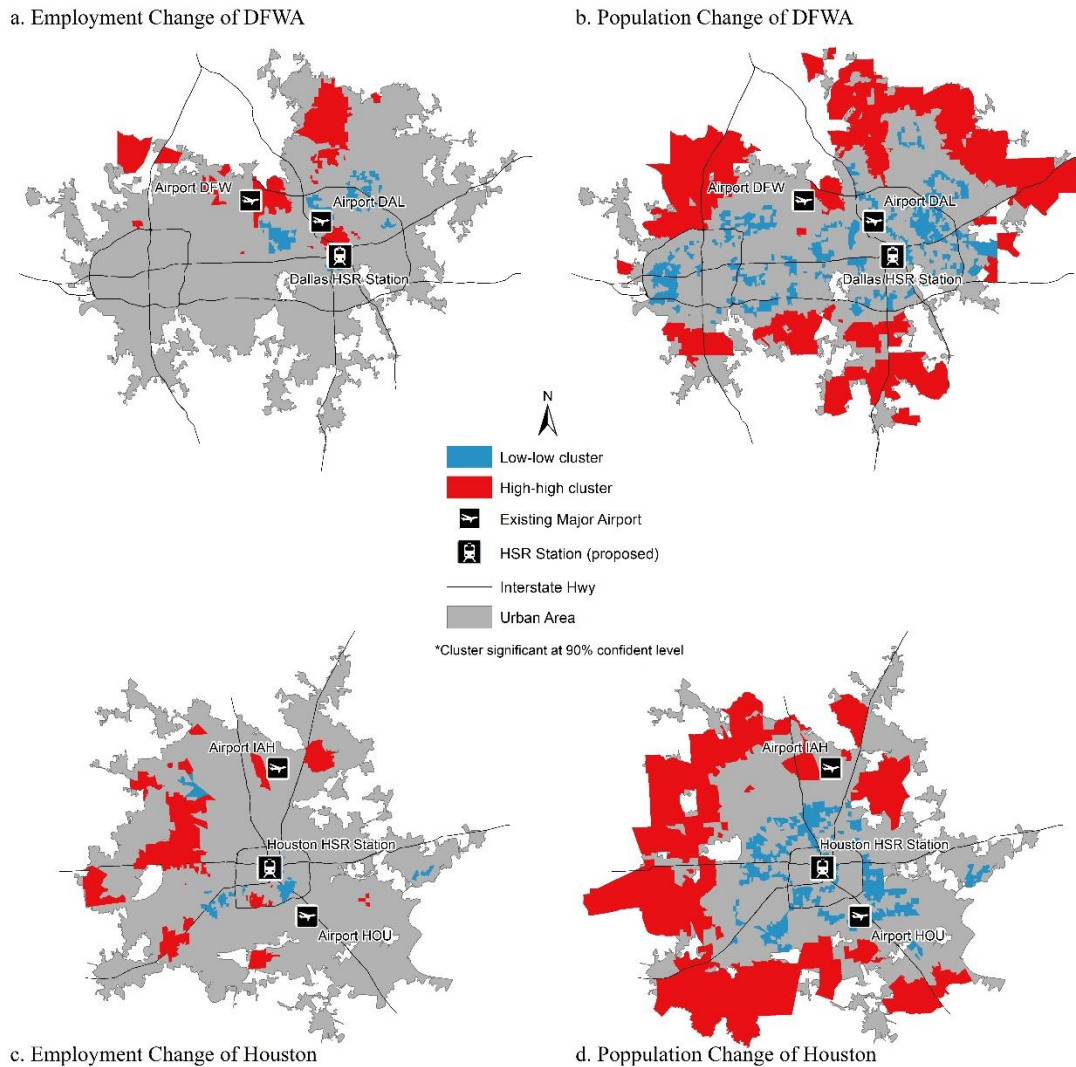
Figure 6.3 Hot spot maps of employment and population change between 2002 and 2014 in DFWA and Houston.

d. A focus on downtown areas

Considering its close proximity to the proposed HSR stations, it is reasonable to believe the downtown areas will be the primary market the proposed HSR service aims to attract. It is thus necessary to take a closer look at the spatial changes of employment and population at the downtown areas (i.e., a one-mile radius circle buffer from the center of the downtown areas) in Dallas and Houston (Table 6.1). For Dallas, the traditional downtown area has seen a decrease of both absolute employment as well as its share of total employment – the total number of

employment decreased by 3.5%, while its share decreased from 5.15% to 4.05%. For Houston, even though the absolute employment count actually increased by 7.88%, the share of downtown declined from 5.54% in 2002 to 4.61% in 2014. The drops in employment share of the downtown regions in both cities are in agreement with previous hot spot maps that indicate a faster growing rate at off city center areas.

Table 6.1 Employment share in downtowns in Dallas and Houston.

	Year	Downtown	Total	Downtown Share
DFWA	2002	119,093	2,313,312	5.15%
	2014	114,924	2,834,823	4.05%
	Change	-3.50%	+22.54%	
Houston	2002	102,277	1877,944	5.45%
	2014	110,336	2391,078	4.61%
	Change	+7.88%	+23.32%	

The temporal trends indicate that while both cities have experienced over 20% increases in employment, downtowns have seen a much lower job increase, or even decrease in employment between 2002 and 2014. Their shares of total employment in the urbanized area is consistently shrinking. This implies 1) the proposed HSR sites, which are located in city centers, will miss out on the fast growing employment sites that are outside of the traditional downtowns, and 2) the overall average access/egress time will increase due to faster employment growth in out-of-downtown regions in both urbanized areas. The impact of the temporal changes in employment and population on the weighted average of access/egress time to different intercity facilities will be discussed in more detail in the next section.

e. **The impact of urban form on HSR development**

Changes in spatial distribution of potential passengers will have an inevitable impact on the overall access/egress time to traveling facilities. This section investigates the impact of employment and population change on the weighted average access time (WAAT) for both the proposed HSR stations and existing major airports in both the DFWA and Houston urbanized areas.

WAAT of business and leisure trips and their differences to both the proposed HSR stations and existing airports in Dallas and Houston are calculated and presented (Table 6.2). Discrepancies in WAAT between the two types of trips are observed in that leisure trips have higher WAAT to all traveling facilities due to the relatively dispersed distribution of population.

Table 6.2 WAAT of business and leisure trips and their differences in 2014 (in min).

WAAT of	DFWA			Houston		
	HSR	AIR DAL	AIR DFW	HSR	AIR HOU	AIR IAH
Business	19.81	22.40	23.13	15.62	22.93	31.26
Leisure	24.04	27.63	27.64	20.17	26.42	34.24
Difference	+4.23	+5.23	+4.51	+4.55	+3.49	+2.98

This research further investigates how the changing spatial patterns of employment and population impact both the absolute and percentage changes of access/egress time to the three intercity travel hubs (Table 6.3).

Table 6.3 WAAT increase from 2002 to 2014 (absolute increase in min).

WAAT change 2002-14		Dallas			Houston		
	Weighted by	HSR	AIR DAL	AIR DFW	HSR	AIR HOU	AIR IAH
Absolute Increase	EMPL	1.21	1.23	0.65	1.4	1.44	0.93
	POP	1.42	1.18	0.70	1.39	1.66	0.64
Percent Increase	EMPL	6.5%	5.8%	2.9%	9.8%	6.7%	3.1%
	POP	6.3%	4.5%	2.6%	7.4%	6.7%	1.9%

From 2002 to 2014, the increasingly dispersed distributions of both employment and population lead to increased average access/egress time to HSR stations and airports, but at different levels. A trend can be observed that centrally located hubs, i.e., proposed HSR stations, Airport DAL, and Airport HOU, suffer more from the increasingly dispersed distributions of employment and population at both the absolute and percentage measures. For traveling hubs that are farther away from existing city centers, such as Airport DFW and Airport IAH, the impact is relatively small. An overall trend is that the closer the hub location is to the city center, the higher impact the sprawling distribution will have on the hub. In other words, the increasingly spreading

out urban form indirectly supports off-center traveling facilities by causing less increase on their overall access/egress time. This is in accordance with the findings from Chapter IV.

Conclusion

Based on the historical LEHD data sets, this research examined the spatial distributions of employment and population in the DFWA and Houston area from 2002 to 2014. Their impacts on access/egress time to both HSR and its competitors (i.e., air transportation) were also discussed. The results reveal that 1) the spatial distribution of employment is more concentrated at city centers than that of population. This means that business trips, which will have origins and/or destinations from employment sites, will have shorter overall access/egress time and will benefit more from HSR than leisure trips in general; 2) even for employment distribution, however, traditional downtowns only account for a small share (less than 6%) of total employment in both area and their share was constantly shrinking during the study period, indicating only a small percentage of employment sites will enjoy the full benefit of HSR trips; 3) from 2002 to 2014, growth of both employment and population happened mostly outside of traditional downtown, resulting in declines of share in both employment and population in the downtown areas. The growth rates in the downtown areas have also been lower than the overall urbanized area, making HSR less justifiable as it will miss out new development outside traditional downtowns. With stations just at/around the traditional downtown areas, areas at the city peripheries, which are experiencing higher growth rate in both employment and population, will have higher access/egress time and people in these areas are less likely to be attracted to HSR services; 4) the increasingly dispersed spatial distributions lead to higher increases in average access time to centrally located HSR stations than to airports in the periphery, which further negates the advantage of HSR travel.

The differences in urban form between countries with HSR (i.e., European and Asian countries) and the United States requires a deeper and more comprehensive analysis of the

benefits HSR can bring in terms of reduced travel time, especially considering the high cost of such systems. Even with the increasingly popular smart growth, new urbanism, and downtown revitalization projects that promote mixed-use development and compact development, this study shows both employment and population are shifting away from traditional downtowns in both the DFWA and Houston urbanized areas. To fully harvest the benefits of centrally located HSR stations, it requires careful design and strategic planning from policymakers to fit proposed HSR projects to reinforce and complement existing and future projects that promote downtown and station-wide development.

CHAPTER VII

CONCLUSIONS

HSR has experienced rapid expansion in European and Asian countries in the last decade.

On the contrary, HSR proposals in the United States keep encountering obstacles and difficulties

that lead to seemingly inevitable failures to initiate any HSR project. The reality remains that

HSR still barely exists in the United States. Acela Express, operated by Amtrak, remains the lone

HSR line in operation to date.

Many factors contribute to the rare existence of high-speed passenger rail transportation

in the United States — among them low overall population density, stiff competition from auto

and air travel, and the lack of institutions and governments that are optimized for centralized

solution are regarded as common ones (Thompson 1994). This research took a detailed look at the

first two major issues, which are low population density and modal competition, from an

accessibility approach. In the contributions section, I will summarize the findings and

contributions of this research, discuss some of the limitations, and list research directions for

future studies. Toward the end of this chapter, I will provide my outlook and suggestions on

future development of HSR in the United States with a focus on the role of urban form.

Contributions to HSR accessibility studies

While previous accessibility studies have primarily focused on either the intra- or inter-

city part of a HSR journey, this research proposes a door-to-door travel time framework that can

simultaneously incorporate both parts and capture the door-to-door travel time for intercity travel.

Given the relatively dispersed urban form that leads to high overall access/egress time, this door-to-door approach is particularly valuable in HSR accessibility studies in the U.S. context. While this research defines and discusses each of the major segments under the door-to-door framework, access and egress times are of particular interest in this research because of their relationship to urban form. Using a simulation-based approach, an in-depth investigation on the relationship between urban form and access/egress time is carried out with an emphasis on modal competition.

To complement the theoretical framework and exploration, as well as to fill the gap that few case studies of HSR accessibility analyses have been carried out in the U.S. context, this research applies the door-to-door framework to the proposed Dallas-Houston HSR corridor through the construction of a multimodal transportation network including HSR, air, and auto. The multimodal network is based on the real-world information and is implemented in a GIS environment. A new catchment area delineation method is developed and implemented based on the door-to-door framework for Dallas and Houston to reveal spatial variations of the accessibility advantages of HSR at the sub-city level over its competitors and provide some insight on HSR planning in the corridor. Lastly, the spatial development trends of urban form in the past decade in Dallas and Houston are revealed with an emphasis on its implications on HSR development in the region.

The results of this study suggests that the dispersed urban form in the United States continues to be an obstacle for HSR development from an accessibility perspective. The accessibility improvement that centrally located HSR stations can bring is heavily negated by the low-density development patterns and weak city centers in U.S. cities. Analyses of the development trends of urban form in Dallas and Houston also show the two cities have become even more spatially dispersed in terms of both employment and population distributions from 2002 to 2014, suggesting centrally located HSR stations will likely miss the opportunity to serve emerging business and residential populations at off center locations.

Some limitations of this research are noted as follows. Conceptually, this study did not focus on identifying how urban form will affect the *niche market* of HSR, defined as the distance range within which a pair of cities would be best served by HSR rather than competing modes considering the levels of urban compactness. This is because even though the impact of urban form on access and egress times has been analyzed comprehensively, there are other segments in an intercity trip, such as on-board travel time and transfer time that are highly variable and will impact the desired distance range at which HSR prevails. The on-board travel time is largely dependent on the actual speed of the rolling stock, and the actual travel time depends on the types of high-speed trains that are adopted. The on-board travel time is also determined by the number of intermediate stops for which the train needs to slow down and stop. Transfer time, which denotes the time it takes for an arriving passenger in the HSR station to find a new mode of transportation to travel to the final destination, is also variable and is dependent on the intermodal connectivity of individual rail stations. Such information is usually impossible to predict before a HSR project is planned. It is because of these hard-to-predict variables that this study cannot derive definitive niche markets based only on urban compactness.

Another limitation, primarily in the case study, is the lack of public transit network and congestion-aware road network when constructing the intracity transportation networks. The absence of public transit as possible supporting modes to HSR is because of the overwhelming popularity of the automobile in both Dallas and Houston. When it does make up a significant portion of intracity movements, public transit can be integrated in addition to auto as an alternative to fulfill access and egress trips based on timetable data. The absence of congestion-aware road network is due to the difficulty of finding such data that are open and publicly available at the urban area level. When such data are available, they can be readily incorporated into the existing framework and implemented in a GIS environment.

Several aspects of this research on both the theoretical and application sides can be further improved in future studies. On the theoretical side, more complicated models of urban

form, such as multi nuclei, urban realm, etc., are becoming popular trends in the trajectory of urban development. These models are essentially more complicated than the monocentric model this research focused on. More effort needs to be devoted to fully address the complexity of these models, as well as to understand their impact on HSR accessibility. On the application side, the incorporation of more time-sensitive and diverse traffic information, such as congestion-aware transportation networks, intracity public transit systems, pedestrian networks, etc. can contribute to a more accurate and inclusive platform for travel time calculation. While such data were historically difficult and expensive to collect, the rapid development of information and communications technology (ICT), in conjunction with the popularity of open data-sharing platforms, have made collection of such data possible through volunteered geographic information (VGI). With the development of VGI, expansions of this research is promising by taking advantage of VGI when collecting time-sensitive traffic data.

Challenges and opportunities of HSR development in the United States

Rail transportation used to be the backbone of this country's transportation system until the early 20th century. While the recent popularity and success of HSR implementation in Europe and Asia has certainly provided extra stimulus for the United States, efforts trying to realize the resurgence of passenger rail in the United States have proven to be rather fruitless. Only until recently were actions taken to make actual progress in HSR development. The start of the construction of a state-wide HSR system in California in 2015 has brought much excitement and hopes for rail supporters in the country. Why are Americans falling so far behind in the development of HSR? Will the United State catch up in the race and what actions need to be taken to do so? Relating to the theme of this research, i.e., the impact of urban form on HSR development, this section draws connections between the findings of this research and the current status of HSR development in the United States. Outlook and suggestions from the author for future HSR development in the United States are also provided.

a. HSR and urban form

Low population density has been regarded as one of the key reasons HSR has not been

the choice for the United States when it comes to intercity travel. More specifically, the United

States does not have a high enough population density to ensure adequate ridership levels for

HSR. The counter argument, however, is that the United States does not have low density all

across the country. Why do regions that have overall high population density (e.g. SF-LA

corridor, Texas Triangle, etc.) not see HSR development historically?

A deeper examination of American cities by this research revealed that it is the low *urban*

density, referring to the relatively low population density in *urban areas*, rather than simply

overall low density at the regional or national level, that is making HSR development difficult.

HSR stations, or rail stations in general, are usually located close to city centers and offer

intercity travel from city center to city center. HSR travel thus have a competitive edge when

comparing to air travel by offering shorter access and egress times. This characteristic of HSR

makes it favor cities that have compact development patterns and have dominant downtowns to

fully take advantage of centrally located facilities.

As cities spread out, the advantage of a centrally located facility diminishes. American

cities are known for their low-density development patterns where dominant downtowns and

public transit systems are rare. Granted, there are outliers like New York Cities featuring

extremely concentrated development and a world-class mass transit system, the fact remains that

most other American cities are so spread out that rail transportation loses its edge in the

competition with auto and airplane due to the spread-out urban form and the lack of adequate

public transit system. American downtowns have also been losing employment and residential

population and struggling to keep their city core alive since the latter half of the 20th century. The

emphases on automobile and highway are among the major reasons that American cities have

dispersed and low-density development patterns. With changes in transportation modes come

changes in urban forms. Before the arrival of automobiles, city dwellers had a much smaller

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activity radius, which implicitly forced a compact and mixed use development pattern that ensures high accessibility by eliminating unnecessary and lengthy trips. When the automobile age came, however, accessibility was realized by higher travel speeds achieved through powerful car engines as well as extensive construction of highway systems within and between cities. The popularity of the personal automobile also brings a high level of freedom in individual mobility – trips are more and more made at the individual level rather than collectively (i.e., via public transit). Compact cities were no longer necessities, as high-speed travel shrinks the space with fast-moving automobiles on highways. Suburbanization kicked in inevitably as people sought to leave degraded urban cores for better and more spacious living environments. American cities, with the assistance of automobile and extensive highway developments, were destined to a future that are characterized by low-density development and declining downtowns.

As this research demonstrates, a centrally placed travel facility suffers more from dispersed urban form by having higher access/egress time. Airports and car converging points, on the other hand, suffer only mildly from a decentralized urban form. A dispersed urban form indirectly encourages the use of airports in the periphery of cities rather than railways in city centers, which reduces HSR's competitive edge and makes it harder for HSR to compete with air and auto.

b. Toward a HSR-friendly future

The landscape of urban and transportation geography in the United States is certainly changing. While automobile and air transportation still dominate the intercity travel market now and possibly in the near future, they are far from flawless, and signs of problems are surfacing. Issues such as congestion have emerged for road and airport transportations and will only become worse for major American cities with increasing populations and urbanization. The idea of suburbanization, that people can afford to live tens of miles away from their workplace, is based on the premise that a person can travel on unobstructed highways at full speed. With the increase

of urban population, however, congestion is becoming a norm in/between big cities and it virtually renders highways into static parking lots filled with helpless drivers. In most cases, expansion of highways will not be a favorable solution because 1) space in urban areas are limited, and 2) wider highways will inevitably encourage/induce more automobile traffic. Being one of the most efficient (in terms of carrying volume per unit of space occupied) transportation modes, HSR can provide a new way of traveling to relieve pressures on the road and at the airports.

Adversities resulting from current urban forms of U.S. cities will inevitably exist in HSR development. Much like a delicate plant, HSR has rather demanding requirements on the environment of its habitat. Intrinsically an intermodal transportation system, a well-designed HSR usually needs support from other mass transit forms to provide feeder services. When compared to cities in Europe and Asia, where HSR has been constructed in recent years, it is obvious that cities with HSR stations usually have extensive mass transit in/around the city to support access to the train stations. The existence of public transit systems in the NEC and SF-LA corridors also helps to explain why the two regions are the first to witness HSR development in the United States. Because of the lack of well-developed public transit systems, HSR proposals and initiatives in Texas, which hosts two of the most sprawled and fragmented cities, Dallas and Houston, are yet to claim actual progress of HSR development in the region.

A lack of promising settings should not be interpreted as a sole obstacle. It can also be taken as a sign of opportunity for something better to happen. In fact, opinions and efforts aiming to revitalize American downtowns have been around as early as signs of downtown decline were observed. Concepts and movements, including smart growth and transit-oriented development (TOD) that advocate better integration of community and transportation with development of mixed-use and transit-oriented downtowns and communities, are seizing momentum in recent years. HSR can be planned carefully to work in tandem with existing proposals of downtown development plans that are usually already in place in major urbanized areas in the United States.

Like any paradigm shifts, changes in urban and transportation planning and travel behavior can take decades to happen. The struggle of HSR development in the United States is a perfect manifestation of the time and effort it takes to make such change. However, through offering high speed connections and high carrying capacities, HSR remains to be an efficient travel mode and could be a solid choice for the United States to alleviate its currently ill-functioning transportation system.

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