Interrelations between Transport Infrastructure and Urban Development. The Case of High-Speed Rail Stations.

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mich stets auf meinem Weg bestärkt. Neben moralischer Unterstützung verdanke ich ihnen das Interesse an der Arbeit mit räumlichen Daten und Karten, und am präzisen Umgang mit Sprache und Argumentation.

Forschung zu „Eisenbahnthemen" wird gelegentlich als etwas „eigenbrötlerisch" wahrgenommen. Das ist nicht ganz von der Hand zu weisen. Die Bestimmung von dynamischen Erreichbarkeitswirkungen von Bahninfrastruktur erfordert zum Beispiel ein Verständnis von Prinzipien der Fahrplangestaltung und zur Historie des Bahnverkehrs, was schnell zu sehr spezialisierten Fragestellungen führt. Hier war ich in der glücklichen Lage mich mit ehemaligen Kommilitonen aus Dortmunder Studienzeit austauschen zu können, welche ebenso ein Faible für den Bahnverkehr haben – Andreas Kühner und Robert Nieberg – die auch bei schwierigen Detailfragen noch mit hilfreichen Informationen aushelfen konnten. Vielen Dank!

Die Fertigstellung der Arbeit überlappte sich mit einer noch vor einem Jahr unvorstellbaren Krise, die viele bisherige Gewissheiten in Frage stellt. Einerseits hat die Verlegung der meisten Arbeitszeit in das heimische Wohnzimmer und die Absage vieler Konferenzen durch die Corona-Krise die Fertigstellung dieser Arbeit womöglich beschleunigt. Andererseits hat sie erhebliche Auswirkungen auf die Nutzung des öffentlichen Personenverkehrs, und berührt damit die Grundlagen der Arbeit. Die Dauer und Nachwirkungen der Pandemie sind zum jetzigen Zeitpunkt noch schwer abzuschätzen. Es kann jedoch davon ausgegangen werden, dass auch in Zukunft ein Bedürfnis der Menschen nach Reisen, zu Geschäfts- und Urlaubszwecken, besteht und womöglich sogar weiterwächst. Herausforderungen wie der menschengemachte Klimawandel sind durch die Corona-Pandemie nur kurzzeitig verdrängt, aber nicht beseitigt. Es ist daher zu erwarten, dass auch in Zukunft dem schienengebundenen Personentransport eine wichtige Rolle im interregionalen Verkehr zukommt, und dass der Hochgeschwindigkeits-Personenverkehr für die räumliche Entwicklung bedeutsam bleiben wird.

München, den 23.01.2021

Summary

Interrelations between Transport Infrastructure and Urban Development – The Case of High-Speed Rail Stations.

High-Speed Rail (HSR) changes the spatial distribution of accessibility, which represents an important locational factor for households and companies, and hence influences urban development in the longer term. The dissertation quantifies and spatialises changes in accessibility through HSR, analyses associated urban development processes, and establishes policy recommendations for sustainable and integrated urban and transport planning near HSR stations. The spatial focus of the research is on Europe, especially on Germany.

Keywords: Urban Development; Transport Infrastructure; High-Speed Rail; Accessibility; Integrated Urban and Transport Planning

Deutsche Zusammenfassung

Wechselwirkungen von Verkehrsinfrastruktur und Raumentwicklung – Am Beispiel von Stationen des Hochgeschwindigkeits-Bahnverkehrs.

Der Hochgeschwindigkeitsverkehr der Bahn (HGV) verändert die räumliche Verteilung von Erreichbarkeit, welche einen wichtigen Einflussfaktor für die Standortwahl von Haushalten und Unternehmen darstellt und somit langfristig die Raumentwicklung beeinflusst. Diese Dissertation quantifiziert und kartiert Erreichbarkeitsveränderungen durch den HGV, analysiert damit assoziierte baulich-räumliche Entwicklungsprozesse, und erarbeitet Handlungsempfehlungen für eine nachhaltige und integrierte Stadt- und Verkehrsplanung um Stationen des HGV. Der räumliche Fokus der Forschung liegt auf Europa, im Speziellen auf Deutschland.

Stichworte: Raumentwicklung; Verkehrsinfrastruktur; Hochgeschwindigkeits-Bahnverkehr; Erreichbarkeit; Integrierte Stadt- und Verkehrsplanung

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List of Abbreviations

AD	Accessibility Dispersion
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung (German Federal Institute for Research on Building, Urban Affairs and Spatial Development)
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur (German Federal Ministry of Transport and Digital Infrastructure)
BVWP	Bundesverkehrswegeplan (German Federal Transport Infrastructure Plan)
CLC	CORINE Land Cover
CORINE	Coordination of Information on the Environment
DAX	Deutscher Aktienindex (German stock index)
DB	Deutsche Bahn (German Railway Company)
DR	Deutsche Reichsbahn (Railway Company of the former German Democratic Republic)
ESPON	European Spatial Planning Observation Network
EU	European Union
GDP	Gross Domestic Product
GHSL	Global Human Settlement Layer
HS	High-Speed
HSR	High-Speed Rail
HST	High-Speed Train
ICE	Intercity-Express
MMR	Munich Metropolitan Region
MVV	Munich Transport Tariff Association
NEG	New Economic Geography
NUTS	Nomenclature des unités territoriales statistiques
RENFE	Red Nacional de los Ferrocarriles Españoles (Spanish Railway Company)
SNCF	Société nationale des chemins de fer français (French Railway Company)
TEN-T	Trans-European Transport Networks
TGV	Train à Grande Vitesse
UIC	Union Internationale des Chemins de fer (International Union of Railways)
UK	United Kingdom
UN	United Nations
VDE	Verkehrsprojekte Deutsche Einheit (German Unification Transport Projects)

Preface

This document is the result of a publication-based dissertation project. As a consequence, certain formal criteria for the thesis document have to be adhered to, most importantly the condition that publications may not be altered or supplemented, but must be rendered here verbatim as published in the journals or edited books. However, this means that reading fluency across chapters cannot always be guaranteed as in monographic dissertations, and some repetitiveness in the introductory and theoretical parts of the chapters is unavoidable. It is hence important to consider each chapter within the framework outlined in the introductory section.

Nevertheless, following previous examples of publication-based dissertations at the Department of Architecture at TUM, for the ease of reading the citation styles across the embedded publications, which varied due to the requirements of the journals, were harmonised. Each chapter contains a separate list of references. Furthermore, the numbering of tables, figures, and equations was harmonised by adding the chapter number as a prefix, to allow a unique identification within the complied thesis.

1. Introduction

Interrelations between transport infrastructure and urban development have engaged numerous geographers, urban and transport planners, historians, economists and others for more than two centuries. Historically, towns and cities have often emerged in locations that were convenient from a transport perspective, such as natural harbours, fords, and crossroads of major trade routes. Such places were advantageous for production and exchange, as they often necessitated the transfer of goods, and offered a high accessibility with different transport modes. With the construction of canals and causeways in the 18th century, the deliberate interference in such locational advantages moved within the bounds of practical possibility in and by the forming nation-states.

1.1. Railway Development shapes Space

The invention of the railways in the early 19th century enormously extended these possibilities. The advent of railways throughout Europe was greeted with great enthusiasm among many observers at the time. Economist Friedrich List argued already in 1838 that "it will be infinitely easier than before for the merchant and factory owner, to expand his business circle and his customers by travelling, to expand or correct his knowledge and concepts of things and relationships, to arrange and carry out joint ventures with people who live in distant places, to settle differences personally, and to find suitable assistants. […] These trips will result in purchases and new facilities, new business connections and ventures" (List 1838: 7, own translation)[1]. He also observed that rail transport – as opposed to canal transport – would be beneficial primarily for passenger travel, including leisure activities and health tourism (ibid.). Likewise, in 1839, an anonymous observer of the railway expansion in England at the time speculated that, "supposing that our railroads, even at our present simmering rate of travelling, were to be suddenly established all over England, the whole population of the country would, speaking metaphorically, […] place their chairs nearer to the fireside of their metropolis. […] As distances were thus annihilated, the surface of our country would, as it were, shrivel in size until it became not much bigger than one immense city" (cited by Schivelbusch 1978: 32). The quotes show that the potential of rail infrastructure to generate catalytic effects, agglomeration advantages, and new economic and urban development had been recognised very early. Both quotes adopt a national, aggregate perspective, but new transport infrastructure is never implemented universally. Hence, its effects are spatially differentiated.

The new railway lines often rearranged the spatial distribution of accessibility on the regional and city scale. Whether a region or a city received a connection to the growing railway network or not could hence have lasting consequences on its locational accessibility advantages for firms and households. Formerly prosperous towns along important thoroughfares could stag-

[1] He went even further in arguing that a fully developed railway network would "abolish war, inflation, hunger, national hatred and unemployment, ignorance, and inefficiency" (List 1838: 6, own translation). The argument that swift and cheap transport furthers the understanding among nations is still frequently used today, e.g. during the recent discussion on air fuel taxes, but must so far unfortunately be described as one of the less accurate of List's prognoses.

nate or even decline when they were bypassed by new railway lines, while previously unimportant villages could experience a strong population and economic growth if they happened to receive a stop, or even become the location of an interchange station. Examples of these processes are numerous throughout Europe – in the German-speaking countries, Hamm, Lehrte, Olten and Treuchtlingen are typical "railway towns" of the industrial age, located at new crossing points of lines. Vice versa, Pforzheim and Heilbronn have suffered from the routing of the first railway lines via the small villages of Mühlacker and Bretten (Köhler and ARL 2007: 70-71). Comparative studies of railway network expansion and urban development in the Netherlands (Koopmans, Rietveld and Huijg 2012) and Sweden (Berger and Enflo 2017) have demonstrated a strong relationship between railway accessibility and urban growth particularly for the end of the 19th and early 20th century.

Railway development also often changed the growth dynamics within city-regions. Whereas most European cities had been limited in their extent by the slow average speed of land-based transport before, the railway enabled the expansion of cities into city-regions, the spatial separation of urban functions, particularly residence and workplace, and an increasing segregation of city-dwellers by social and economic status. London, the capital of the most industrialised country of the time, grew from barely 4 km in diameter as late as 1800 to a metropolitan region that covers the entire South-East of England today, which would have been impossible without the London underground and the regional rail transport system (Levinson 2007). The railway enabled the first wave of suburbanisation.

Finally, railway stations often influenced urban development on a local level. For reasons of practicality and economy, stations were typically constructed on open terrain at a certain distance from the urbanised areas they were supposed to serve. Subsequently, the main connecting streets between the new stations and the traditional urban cores became prime representative addresses for businesses and shops, in competition with traditional locations (Bodenschatz 1983; Köhler and ARL 2007: 72). The "station street" offered the locational advantages of both, the local agglomeration and the connectivity via the new transport network. At the same time, the private, and later state-owned railway companies strived for outstanding architectural representation of their new importance in the design of their main stations, described already by contemporaries as 'cathedrals of modernity' (Thomsen 2010: 17). The stations became not only the main entry points to the cities and important nodes of the regional and local transport network, but also took on a role of anchors of urban life beyond their transport function, leading to a reorganisation of the spatial structure of cities.

Simultaneously, the enormous spatial requirements of the new infrastructure and its linear alignment typically created 'front-' and 'backsides', with consequences for land use distributions. "Unwanted", industrial uses were often located on the opposite side of the tracks, as seen from the city centre. Consequentially, Baumeister (1876: 134), the first author of an urban planning handbook in Germany, favoured terminal stations as opposed to through stations due to their better integration with the urban fabric. Urban and railway development entered an ambivalent relationship of mutually reinforcing growth, but also of increasing conflict. At the same time, rail infrastructure planning has never been detached from the existing distribution of population and economic activity. The – initially private – railway companies strived to connect the most populous and industrial areas first, which promised the highest demand and profit. Hence, this dissertation is concerned with the “interrelations” between urban development and transport infrastructure, rather than just one-sided “impacts” of infrastructure.

1.1.1. Competition from New Transport Modes

Since the 1950s, the private car and air travel have largely replaced the role of rail transport for commuting on the one hand and long-distance travel on the other in most Western European countries. In Germany, for example, the modal share of rail on passenger transport volume dropped from 36,4% in 1950 to 6,2% in 1989, while that of individual motorised traffic rose from 35,5% to 82,4% and that of air transport rose from 0,1% to 2.4% (BMV 1991: 312-315). Rail network length shrank by 10% (BMV 1991: 78-81). Within city-regions, the car has made ubiquitous urbanisation possible, with detrimental consequences for quality of life and the environment through increased urban sprawl, green space fragmentation, emissions, and deterioration of public space (Ewing 1997). Air travel has shifted attention of urban planners away from railway stations to airports, recognisable in the variety of planning concepts recently developed, from “airport cities” (Güller and Güller 2003), and “airport regions” (Droß and Thierstein 2011; Michaeli, Salewski and Frei 2011), to “aerotropolises” (Kasarda 2000). The neighbourhoods around main railway stations in large cities had in many cases lost their attractiveness for local businesses and residents, becoming instead associated with decline and crime (von Gerkan 1996: 19).

However, the decline of passenger rail in Europe was in fact often only a relative one. In Germany, for example, total passenger rail transport volume remained largely stable throughout the second half of the 20th century, and long-distance travel volume even increased between 1950 and 1990 (BMV 1991: 318-311). Passenger rail transport never fully disappeared. Then, several social, economic, and technological developments, starting already in the 1980s, have called the unchallenged triumph of the car and the plane into question, and contributed to a trend reversal.

1.1.2. Reinvigoration of Passenger Rail in the 21st Century

Growing political and societal awareness of anthropogenic climate change and the negative ecological consequences of both car-dominated urban and transport planning and short-haul flights have meant that the comparative advantage of passenger rail transport with respect to emissions (Leboeuf 2016: 407; Schwarzer and Treber 2013) has received more recognition by decision-makers and consumers. In addition, the economic base in developed countries is shifting towards tertiary, knowledge-intensive branches (OECD 1996), which are strongly associated with urbanisation and spatial clustering (Thierstein et al. 2008: 1129). The city-centre orientation of passenger rail, as well as the availability of travel time for uninterrupted work, turn it into an attractive means of transport in the knowledge economy.

Most importantly for this dissertation, technological innovations have contributed to a reinvigoration of passenger rail as a transport mode in the recent decades. Particularly in Asian and European countries, the recent construction of new, specially purposed rail lines for very high speeds has given passenger rail transport a new impetus.

Such High-Speed Rail (HSR) lines improved the competitiveness of rail over air transport (UIC 2009) on distances of up to about 800 km or four hours travel time (Figure 1-1). Significant ridership growth, often beyond initial estimates, as well as mode shift from both car and plane, but also conventional rail to HSR have been convincingly documented in literature (e.g. Bonnafous 1987: 129; Albalate, Bel and Fageda 2015: 171; Dobruszkes 2011).

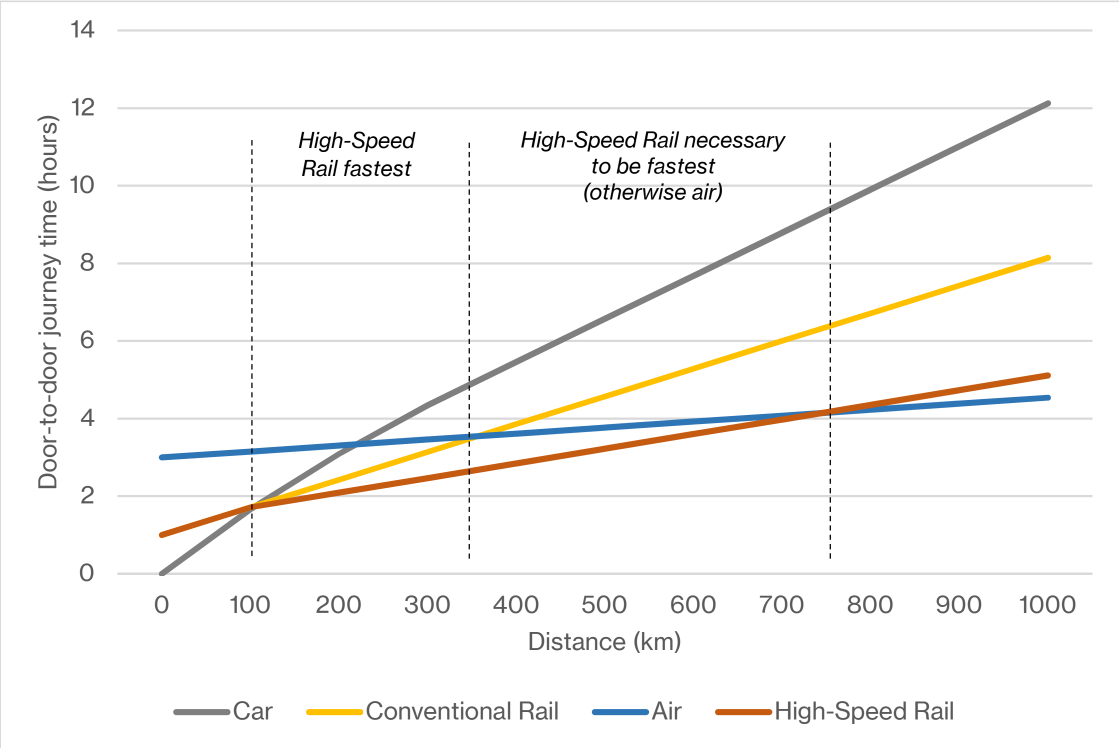

***Figure 1-1**: Competitive advantages of different travel modes in terms of overall door-to-door journey time (adapted from European Commision (2010: 9); Steer Davies Gleave (2004: 23))*

The combination of the above mentioned factors has meant that investment in (high-speed) rail has become a preferred policy option for public investments, as it potentially conforms to the goal of decoupling emissions and economic growth, without relinquishing growth altogether. With this background, the current Covid-19 stimulus packages can be expected to lead to further HSR investment, despite the initially detrimental consequences of Covid-19 on public transport usage. The Council of the European Union has declared 2021 to be the "European Year of Rail" (Council of the European Union 2020). In Germany, overall rail network shrinkage has come to a halt in the last decade, and the mode share of passenger rail has increased again, to 8.6% (BMVI 2020: 52-53, 221).

Simultaneously, the debate on the spatially differentiated impacts of HSR has resurfaced. Like in previous phases of railway development, there are again high expectations by some national and local actors, that new transport infrastructure can be used as a targeted policy tool for regional and local economic and urban development. The scientific review of this relationship has remained inconclusive at best, however, as the following sections will show.

This dissertation examines the interrelations between transport infrastructure and urban development with a focus on the local scale, using the case of newly constructed HSR and express rail stations. It follows three goals: to quantify and map accessibility changes induced through

HSR, to analyse urban development processes around the entry points to the new transport system, and to contribute to policy recommendations for sustainable integrated urban and transport planning related to HSR stations. The dissertation focuses on European cases, and particularly on Germany, since there have been few studies with a focus on the country so far.

This introduction is structured as follows: First, the main characteristics of HSR as a new transport mode are briefly reviewed. The second section presents an overview of important theoretical concepts that can be applied to explain interrelations between transport infrastructure and urban development. The third section surveys results of previous empirical studies on the topic, particularly regarding HSR, followed by the identification of research gaps. The next section details the research questions and hypotheses of this thesis. The findings of the previous sections are condensed into a spatial impact diagram that summarises them visually. Finally, the structure of the dissertation is presented, together with the varying methodological approaches of the chapters.

1.2. High-Speed Rail: Definition and Characteristics

While some academic publications use the term High-Speed Rail to describe a certain train category, irrespective of infrastructure and actual speed (e.g. Heuermann and Schmieder 2018; Evangelinos, Hesse and Püschel 2011), this dissertation uses an infrastructure-oriented definition of HSR, based on the widely applied EU definition of HSR as newly constructed lines that allow speeds of 250 km/h or more, and upgraded lines for speeds of 200 km/h or more (European Council 1996) – compared with a usual top speed of 160 km/h for conventional rail lines. Nevertheless, to achieve the desired speed, dedicated HS trainsets are often necessary (Figure 1-2). In addition, for this thesis, express rail lines in urban areas are also included in the case of strong travel time differentials, and thus accessibility changes.

Figure 1-2*: A High-Speed Train (TGV InOui) in Valence TGV station, France. The station has been constructed on open space at about 10 km distance from the town centre and the existing main station (author)*

HSR has been implemented starting in the 1960s with the Shinkansen in Japan (Tokyo-Osaka), and from the 1980s onwards in several European countries, beginning with France (1981, Lyon-Paris), followed by Germany (1991, Hannover-Würzburg), Italy (1992, Rome-Florence), and Spain (1992, Madrid-Seville). Even though HSR was soon able to regain market shares for passenger rail from car and air transport, initially this was not the main motivation for constructing HSR lines, at least in France. Rather, rail companies sought for ways to expand capacity for freight transport on congested conventional lines by transferring passenger rail away from them (Hoffmann 1985: 204-206). However, after the success became evident, the motivation shifted. Design speeds have continuously increased – some recent HSR lines are equipped for speeds of up to 350 km/h. As of 2020, the HSR network in China has the greatest combined length, after a decade of fast growth. Further countries with HSR conforming to the EU definition in Europe are Austria, Belgium, Denmark, the Netherlands, Russia, Switzerland, Turkey, and the United Kingdom (UK), in addition to the countries already mentioned. In the EU, as of 2020, there are about 10,830 km of HSR lines in operation and another 2300 km currently under construction (UIC 2020), with more lines in the planning phase. Despite multiple project proposals, for example in the Los Angeles-San Francisco corridor, no HSR has been constructed in the United States so far.

The chosen network structures and parameters for HSR vary widely across countries, reflecting different political preferences and the still dominant role of the state for railway organisation. In some countries new HSR lines are "fully mixed" (Campos and de Rus 2009: 21) and integrated with the existing conventional network, i.e. they can be used by slower regional and even freight services as well, while HS trains can also use the conventional network. This improves the versatility of the network, but leads to increased construction costs (e.g. Germany, Austria). In other countries the HSR network is mostly or even entirely separated from the conventional network (e.g. Spain), mostly due to the technical incompatibility (gauge width, electricity supply) of the existing network with the international standard, effectively resulting in the construction of a second, separate and new rail network. The question whether HSR actually represents an advancement of an existing mode or an entirely new mode of transport hence has different answers, depending on the national situation. Between the extremes, different combinations are possible (Figure 1-3).

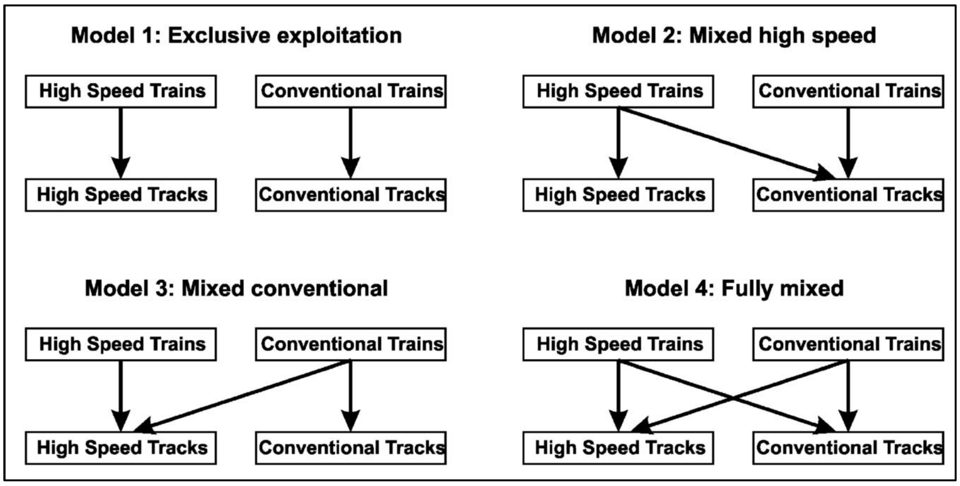

Figure 1-3: *HSR models according to the relationship with conventional services (Campos and de Rus 2009: 21)*

Differences also exist with respect to network structure. Figure 1-4 shows a map of new HSR lines and stations conforming to the EU definition (new lines speeds of 250km/h or more) currently in service or under construction in Europe. Following both economic and political considerations, many unitary countries with a single, dominant metropolis exhibit radial HSR networks centred on the main city (e.g. France and Spain), while in federally-organised countries and/or countries with a polycentric urban structure, HSR lines often follow a grid pattern (e.g. Germany, China). A third type is the HSR corridor or spine, which can be found in countries with a linear geography (e.g. Italy, Japan).

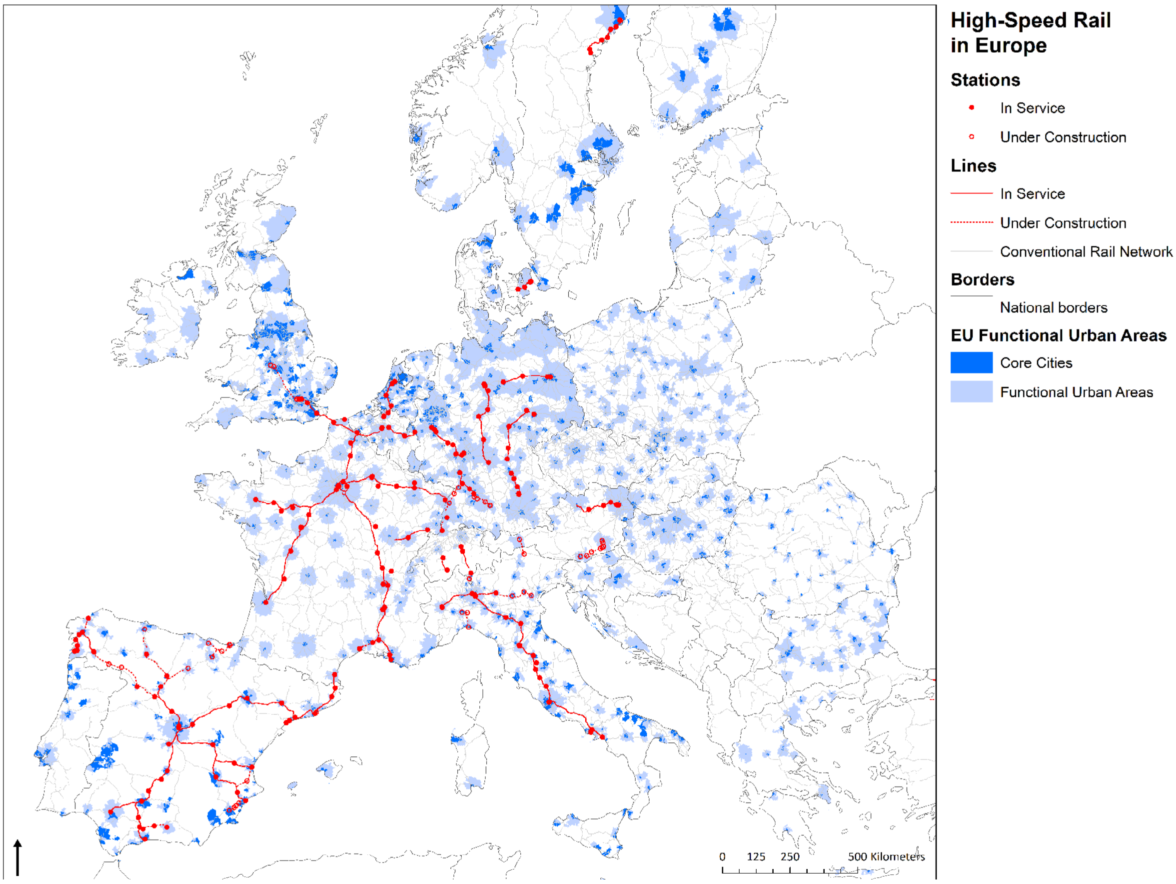

Figure 1-4: *HSR lines for speeds of 250 km/h and more, and their stations, in Europe, 2020. Source: author; Geodata by Eurostat (2020), Openstreetmap Contributors (2016) (Open Database Licence), DB (2019)*

The chosen service models, population geography, and political considerations are also related to station placement policies, which in turn can play a role for urban development: in major cities, existing (terminus) stations are usually utilised for HSR (e.g. Paris Montparnasse and Madrid Atocha stations). However, even in smaller cities, traditional inner-city main stations are often integrated into the HSR network in polycentric countries with the consequence of better access for less populous and peripheral regions (Givoni and Banister 2012), but increased overall journey times for longer distances (for example, the stations in Fulda, Göttingen, and St. Pölten). In contrast, in sparsely populated countries with only few large cities, intermediate stops are predominantly constructed in "greenfield" locations out-of-town, leading to longer access and egress journeys but higher average speeds on the system, such as in Montpellier, Reims, and Reggio Emilia (see chapter 4). This shows that the alignment and station positioning of HSR is never entirely "technical" and "neutral", but inherently political as well.

Only relatively late, have the separate national HSR networks in Europe been partially connected and integrated, also incentivised by the Trans-European Networks (TEN) programme of the European Union (Vickerman 1997: 22). These corridors play a major role for freight transport as well (Drewello and Scholl 2016). However, several planned connections are still missing, such as the Lyon-Turin connection (Thierstein, Erhard and Droß 2013), which faces strong opposition by local citizen initiatives. Moreover, recent EU policy encourages the multimodal integration of HSR and air transport through HSR stations at airports. This has been implemented at several major hub airports (e.g. Amsterdam, Frankfurt, and Paris). Despite competing on short and mid-range distances, HSR can act as a feeder service for long-distance flights (Givoni and Banister 2006: 388; Lijesen and Terpstra 2011), thereby widening the role of HSR stations as gateways to air transport. Potential future applications of HSR also include long-distance night trains (UIC 2013).

The construction of HSR lines is politically controversial. Construction costs are often substantial and vary widely depending partly on the nature of the terrain (Givoni 2006: 608; Campos and de Rus 2009: 23), while running costs of rail lines generally increase with speed. New lines cause noise, and require the sealing of agricultural and forest areas, which can cause the dissection of open space. Several transport planning experts argue that instead of investing in HSR, network operators should invest in upgrading and expanding the conventional network (e.g. Monheim and Nagorni 2005). At least, HSR lines should be well integrated with the conventional network to allow effects to trickle down (Givoni and Banister 2012).

Overall, only two HSR links in the world are said to be completely internally profitable: Tokyo-Osaka, and Paris-Lyon (Ryder 2012: 303). For Paris-Lyon, Vickerman (1997: 26) mentions a 12% financial rate of return. However, internal economic profitability has to be differentiated from social profitability, which includes positive external effects, such as emissions savings, increased productivity, and – importantly in the context of this thesis – second-round effects on urban development. Such external effects are currently not considered in standard cost-benefit analyses (Blanquart and Koning 2017: 338).

In the following chapter, different theoretical concepts are briefly introduced that provide a background to understand such potential changes of the urban environment as a response to transport infrastructure improvements, particularly with respect to the local scale.

1.3. Theoretical Lenses for Interrelations of Transport Infrastructure and Urban Development

A range of theoretical lenses from different disciplines, such as economic geography, urban economics, and urban planning, can be used to conceptualise the interrelations of transport infrastructure and urban development. Urban development, in this thesis, is defined as a change of the built environment, such as the construction and renewal of buildings and the expansion of urban space – usually, but not necessarily simultaneously with local or regional economic development. The theoretical lenses differ in their formalisation and the spatial scales they cover. In addition, it is necessary to differentiate between a spatial-economic perspective that attempts to discover regular cause-and-effect patterns of development in a market-based land use environment, and a normative planning perspective that formulates what should happen, on the background of certain pre-defined goals, particularly in terms of sustainability. In the following chapter, each concept is briefly revisited and its consequences for HSR outlined.

1.3.1. Regional Growth and Development Theories

Regional growth and development theories are used in urban economics and economic geography. They are concerned with the questions why certain regions grow faster than others do, and whether disparities between regions increase or decrease. They typically rely on uniform-abstract (Capello 2000) models of space, with the consequence that they make no statement on discrepancies within regions. Neoclassical trade theory holds that specialisation of and trade between regions makes all participating regions better off, even if one of the regions is more productive for all products (Ricardo 1817). Accordingly, transport improvements that reduce trade barriers between regions are beneficial for overall wealth, but might lead to increased specialisation. The standard neoclassical theory of regional development furthermore conceptualises production factors labour and capital as mobile and attracted by regions in which they are more productive. Initial imbalances of capital and labour among regions, and hence unequal wages, rents, and interest rates are expected to converge 'automatically' over time (Borts and Stein 1964), raising welfare for all regions. Persistent inequalities are, in this view, partially the result of barriers to the free movement of production factors (Barro and Sala-i-Martin 1992). One way to remove them would be by constructing improved transport infrastructure.

Opposed to the neoclassical regional development model are theories that imply diverging trends between regions, such as polarisation theory (Myrdal 1957) or, more recently, New Economic Geography (Krugman 1991; Puga 2008; Lafourcade and Thisse 2011). These encompass multiple equilibria, cumulative causation, and path dependencies, which can result in persistent regional differences and further concentration of firms and workers in already successful regions. Under these frameworks, a good transport infrastructure endowment and high connectivity with neighbouring regions might mean faster growth for a region, but improving the connection between two regions leaves the initially weaker region ('periphery') more vulnerable to competition from the already more productive ('core') region (Crescenzi and Rodríguez-Pose 2008: 62; Puga 2002). The periphery can be deprived of its industries and served from the core, which in turn can extend its market area. In this view, improving transport infrastructure might in fact be detrimental for a peripheral region. In view of the danger of such "straw effects" (Ottaviano 2008: 27), the ability to balance economic development across regions through HSR has been met with strong scepticism (e.g. Plassard 1994). Lutter, Pütz and Spangenberg (1993: 37) accordingly suggest improving accessibility specifically only in those peripheral regions that already show a high economic performance.

It is hence disputed whether HSR leads to a mutually beneficial development between connected regions, potentially even with disproportional benefits for previously disadvantaged regions, or if it further weakens the region with an inferior starting position, to the benefit of the stronger region. Indirectly, these relationships influence urban development at the local level as well.

1.3.2. Monocentric City Model

Despite the primary character of HSR as an inter-regional transport mode, both its use in practice and recent academic studies (e.g. Guirao, Casado-Sanz and Campa 2018; Moyano 2016) show that under certain conditions, it also has the potential to influence functional relationships typically considered as being contained within (functionally defined) regions, particularly commuting. By doing so, it extends the region itself. The monocentric city model (Alonso 1964) can serve as an explanatory base for transport-land use interactions within regions. It describes the distribution and evolution of local land uses according to accessibility. Here, a physical-metric perspective on space is adopted and both commercial and residential uses are explicitly modelled. It is based on the observation that users of space constantly trade off commuting costs to a (single) centre and land prices. As each parcel of land can only be used by one single bidder this results in concentric rings of uses around the centre, sorted by the willingness and ability to pay for proximity to it. The opening of a new public transport infrastructure between the centre and the periphery unevenly 'compresses' space along the axis, resulting in a shift in the demand, value, and ultimately use of land. Stations on such lines become attractive poles for residential suburbanisation, as they combine relational proximity to the centre with (initially) lower land prices (Figure 1-5).

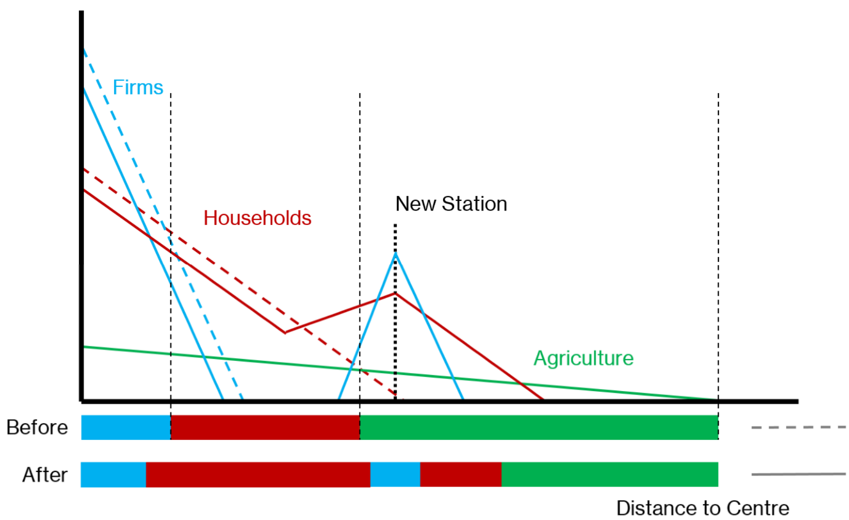

Figure 1-5: *Land uses as a function of distance to centre in the monocentric model of Alonso. The layers at the bottom signify the "highest bidding" land use at a certain distance from the centre (drawn by author)*

The assumptions of the model can be linked to the theory of "constant travel time budgets" which stipulates that households are only willing to invest a certain amount of time per day, usually around one hour, for travel, particularly for regular commuting. Improved infrastructure hence cannot reduce commute times in the long run, but leads to longer commute distances (Zahavi and Ryan 1980; Marchetti 1994). Hence, HSR has the potential to integrate small and medium-sized cities in a city-regional context which were too far away from the central city before (Garmendia, Ribalaygua and de Ureña 2012: 26; Garmendia et al. 2008: 249), but also to spur suburbanisation (cf. Figure 1-6). Likewise, if a station is close to an existing commercial centre and/or represents a node of high accessibility it can attract more firms after a network expansion, due to their high willingness to pay for such locations, as for example Kreibich (1978) has found after the installation of the Munich express rail system. Land value changes are one way to measure the quantity of such effects.

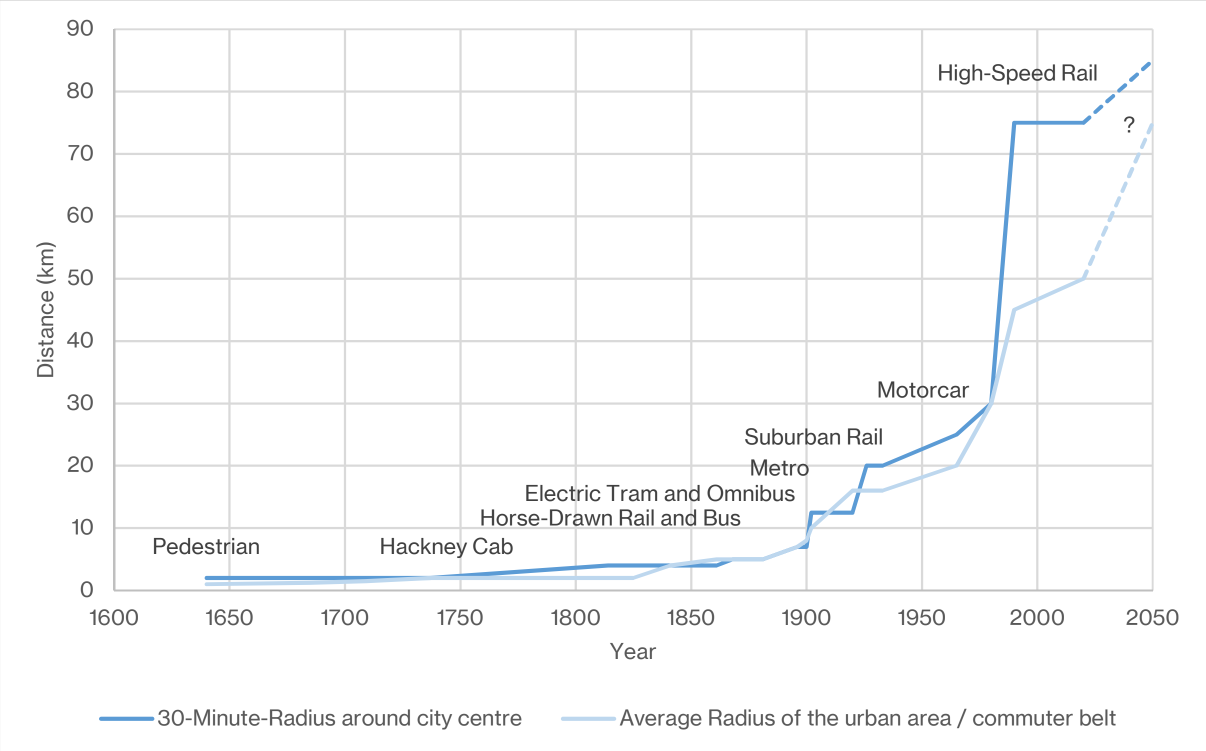

***Figure 1-6**: Urban expansion and transport systems (adapted from Lehner (1966)).*

Classical urban land use/transportation models, as embodied by the "transport-land use feedback cycle" (Wegener 1995: 158), describe these relationships systematically and are often based on an Alonso-type of land use model (Figure 1-7). However, they typically rest upon the assumption that total population and employment within a region are given, and they model distributive effects within a region while taking into account neither generative effects nor interregional movements. In order to address such questions, urban transport/land-use models and interregional trade and development models should be better linked (Rietveld and Bruinsma 1998: 96).

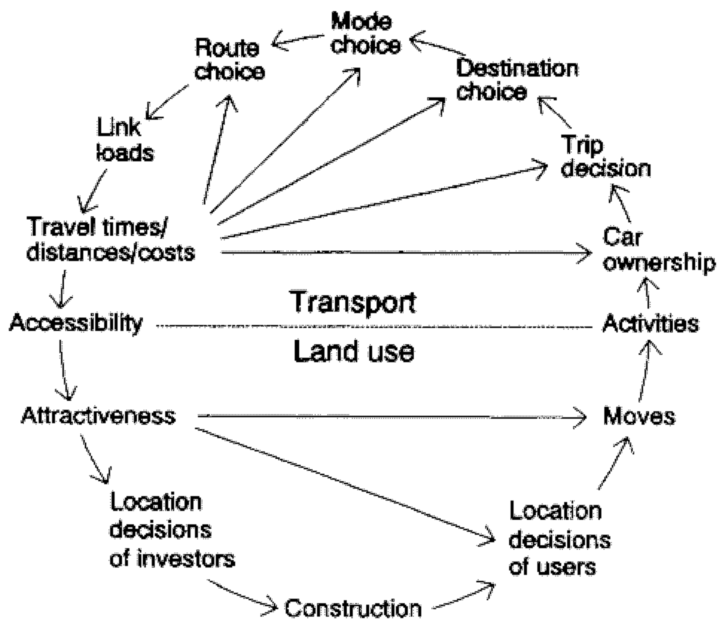

Figure 1-7: The 'land-use transport feedback cycle' (Wegener 1995: 158)

1.3.3. Agglomeration and Network Externalities

Moreover, the monocentric model becomes increasingly difficult to apply. While on the one hand, globalisation and increasing importance of the knowledge economy contribute to a concentration process in metropolitan areas (Krätke 2007; Sassen 2002), there is a simultaneous tendency of regionalisation within them (Soja 2015; Münter and Volgmann 2014). Within the metropolitan regions, this process generally has a deconcentrating effect, but at the same time, it is accompanied by small-scale concentration processes of economic activities, in the course of which new economic centralities or clusters emerge outside the traditional Central Business Districts (CBDs) of the core cities. These are varyingly called urban sub-centres (McMillen 2001; Krehl 2018), new economic cores, clusters, or poles (Burdack 2006; Münter and Volgmann 2014), or edge cities (Garreau 1991) - for an overview of continental Europe see Bontje and Burdack (2011). At the same time, the location factors of households and firms are becoming more diverse (Glaeser, Kolko and Saiz 2001). As a result, the assumption of a single centre of interest to firms and households becomes less realistic. Instead, polycentric urban-regional spatial structures with complex interweaving patterns are emerging (Anas, Arnott and Small 1998; Parr 2005; Hesse 2010). In this way, peripheral locations can become attractive for firms while central locations are preferred by double-income households. Consequently, urban systems are more and more characterised by out-commuting (Heuermann and Schmieder 2018: 360), super-commuting (Pütz 2015: 3), and tangential commuting relations. Hence, a relational perspective is useful to complement classical location-based models in describing changes on a local scale. This can be conceptualised as the integration of agglomeration and network externalities (Meijers, Hoogerbrugge and Cardoso 2017; Bentlage 2014; van Meeteren, Neal and Derudder 2016; Lüthi 2011).

Agglomeration externalities or economies (Marshall 1930) are additional productivity gains a firm realises when it is located close to other firms. In their standard definition, they consist of better labour matching and pooling, improved input-output linkages, and knowledge spillovers, and can occur within certain economic branches (localisation economies) or generally (urbanisation economies). New or improved transport infrastructure does not simply reduce travel times for existing users of a service, but increases the potential of opportunities for interaction, i.e. accessibility (Hansen 1959), through a raised "effective density" (Blanquart and Koning 2017: 340) of firms and households. Firms profit from the public service as a positive externality (Axhausen 2008: 5; Fröhlich, Tschopp and Axhausen 2005: 385; Biehl 1986). As such, agglomeration economies count among the long-term, "catalytic" effects of transport infrastructure, as opposed to the direct, indirect and induced effects during the construction phase (Hujer 2008: 23). Even though the substantial multiplier effects of public infrastructure found in the seminal paper by Aschauer (1989) have been relativised by later studies, elasticities of productivity to increased public transport accessibility on a national scale in the range of 1-2% have been confirmed e.g. for Switzerland (Axhausen et al. 2015: 12). More than on a national scale, agglomeration economies are efficacious on a local scale with the close proximity of actors. Axhausen et al. (2015: 12) find elasticities of up to 4% in urban areas, while Graham (2007) describes elasticities of up to 19% for service sector firms in London.

At the same time, long-distance public transport stations represent nodes in the globalising "space of flows" (Castells 1996) which are often better linked among each other than with their hinterland. Such nodes offer systemic accessibility as a scarce resource. By reducing the transportation costs between two such nodes, HSR contributes to the emergence of "network externalities" (Capello 2000) for firms, that can effectively complement or partially substitute localised agglomeration externalities (Meijers, Hoogerbrugge and Cardoso 2017), particularly for firms in remote areas (Andersson and Karlsson 2004). For example, firms can harness knowledge exchange at fairs and conventions (temporal proximity) to build "global pipelines" in addition to "local buzz" (Maskell, Bathelt and Malmberg 2006). HSR stations function as entry points to such networks.

Specifically, locating close to an urban HSR station can allow firms to profit from both the local and regional agglomeration economies and the HSR-generated interregional network economies, especially when HSR also serves as a feeder service to the air transport system (Givoni and Banister 2006). Particularly urban, tertiary sector firms with national and international orientation as the vanguards of the future economy, such as consultancies (Bonnafous 1987: 135), the information-based economy (Sands 1993: 1) and knowledge intensive firms (Thierstein et al. 2008; Chen and Hall 2011) value the opportunity for a high number of local face-to-face contacts and personalised knowledge exchange, while at the same time profiting from the "overview externalities" that networks provide (van Meeteren, Neal and Derudder 2016: 71). In this way, HSR can give rise to polycentric mega-city regions (Hall and Pain 2006) of interlinked and specialised centres.

1.3.4. Urban Planning and Station Design

While the previous concepts attempt to provide models for a 'quasi-automatic' development of space as a response to changes in accessibility, planning concepts are concerned with normative goals of future urban development. Urban and regional planning assesses the current spatial structure on the background of a desired (future) state, and devises methods and plans to proceed in the direction of this desired state. The desired state is not only determined by planning itself, but also framed by societal norms and objectives. For more than two decades sustainability is now the main leitmotif for urban and regional planning throughout Europe and beyond (UN Habitat 2009). Sustainable urban and regional development attempts to reconcile the economic, social, and ecological requirements for land use, including responsibility for future generations (Lendi 1998). This translates into different sub-goals and planning concepts in the area of public transport (Table 1-1) which are not always in line with the spatial-economic development patterns described previously.

Spatial scale	Theoretical concept
National, Regional	Balancing and growth objectives of comprehensive regional planning Central Place concept
Local	Integrated transport and land use planning Transit-oriented development Station design

Table 1-1: *Important planning concepts regarding the interrelations of transport infrastructure and urban development (author)*

On a national scale, comprehensive spatial planning commonly follows both a balancing and a growth objective (Scharmann et al. 2020: 2). Increased regional imbalances, as suggested by the NEG, would run counter to this objective, while an expansive role of HSR could mean that HSR can serve as a potential tool to pursue a balancing of opportunities across regions. At the same time, HSR has the potential to support, but also to run counter to the aims of the system of central places, which continues to form the basis of regional planning in Germany and beyond (Hoffmann 1985: 50). In its current implementation in Germany, HSR only partially conforms to the Central Place designations, as not all higher-order centres are served equally, while some centres of lower designation have received HSR access if they happened to be located on an axis between higher-order centres. It has been argued that HSR primarily serves the growth objective due to its affiliation with a logic of metropolitan competition and re-hierarchisation of space (Stiens 1993: 899; 1992: 299), at least as long peripheral regions are not served. It hence seems that HSR requires an advancement of the classical, location-based Central Place concept.

1.3.5. Integrated Urban and Transport Planning

On an intra-regional scale, polycentric, dense, and mixed-use development around public transport stations is generally accepted as sustainable. Such "transit-oriented development" reduces access and egress times for users, thereby minimising their propensity to use the car, which is beneficial from an environmental and social perspective (Newman and Kenworty 2015; Newman and Kenworthy 1989). At the same time, it contributes to the profitability of public transport services. Furthermore, residential areas around stations enable social surveillance ("eyes on the street") which improves perceived security and makes communities more liveable (Jacobs 1961). Even though such a development might mean the conversion of open space into building land, it can at least considered preferable to less dense car-based development, which causes even more sprawl, in the case of growing metropolitan regions (UN Habitat 2009). Hence, rail stations as 'nodes' of accessibility should also be considered as 'places' for dense, mixed use development (Bertolini 1999). The integrated planning of land use and transport strategies represents an important cornerstone of sustainable urban development (Scholl 2016: 16). These principles can be applied to local public transport, but also to high-speed rail stations (Kim, Sultana and Weber 2018: 135): Since they typically provide a disproportionately higher level of accessibility than a smaller, regional train station, accordingly they should all the more be cornerstones for urban development.

Lastly, the design of a station itself is an important object of planning and can likewise influence urban development in the station surroundings beyond the accessibility provided by it. Together with the construction of new HSR lines, railway companies often reconstruct or upgrade existing stations along the line to emphasize the quality of the new service and to recast the image of stations, sometimes involving the commissioning of 'star' architects. Examples include the new or refurbished stations at Lyon Saint-Exupéry and London Waterloo (Jencks 1995) or Rotterdam (Trip 2008a). On the one hand, when successful, they become an attractive urban space that is not only used by the rail customers, but by the urban population in general, with positive image and identification effects on the neighbourhood. On the other hand, this can also mean displacement and gentrification. In addition, such urban mega-projects (Peters and Novy 2012) often suffer from cost overruns and limited public participation.

In some cases, station renovations are furthermore necessitated by technical parameters of the new HSR service and expressly justified with urban development objectives, such as railway land becoming available for construction. The controversial project "Stuttgart 21", the replacement of an above-ground terminus station with an underground through-station, is probably the most well-known example in Europe (Novy and Peters 2012; Krüger 2012). In other cases, (main) stations have been relocated within cities (e.g. Kassel-Wilhelmshöhe) or towns have received (a long-distance) rail access for the first time. In all these cases the design of the station itself and its connectivity to the surroundings and other forms of public transport can play a role in both the perceived attractiveness of the service and urban development around the station, and the dimensions of "node" and "place" should be extended by "design" (Vale, Viana and Pereira 2018).

1.4. Previous Findings on HSR and Urban Development

After revisiting important general theories on the interrelations between transport infrastructure and urban development from the domains of economic geography and planning, the following chapter reviews previous empirical literature on the matter with a special focus on HSR.

According to Melo (2019) two main groups of studies on the spatial outcomes of HSR can be differentiated: (a) studies on the changes of accessibility (market potential) caused by HSR, and (b) studies on the consequences of such accessibility changes on a range of output variables, such as GDP, population, or land uses. As both aspects are crucial for this thesis, the chapter follows this distinction: First, results of empirical studies on the actual accessibility changes through HSR are presented, and second, the studies on their impacts.

A quantitative citation network analysis[2] of journal articles on the impacts of HSR accessibility changes furthermore shows the existence of three rather separate clusters of articles that largely correspond to disciplinary boundaries: an economic geography cluster, an urban economics cluster, and a tourism studies cluster. Only few articles are cited by other articles from more than one cluster, among them the paper of Bonnafous (1987) which represents one of the first international scientific publications on the topic and the review paper by Vickerman (1997). The clusters also coincide with a focus on different spatial scales. Articles with an economic and tourism studies background mostly focus on effects in and between regions, while those from geography are more concerned with local effects. The literature on the regional scale is far more numerous than that on the local scale.

Hence, this distinction is used to structure further the second part of this section by spatial scales. Due the focus of this thesis on the local scale, the literature on the regional scale will only briefly be described.

1.4.1. Accessibility Changes through HSR

The primary scale to measure accessibility changes of HSR is the regional scale as HSR is primarily an inter-regional transport mode. There is a richness in literature on regional accessibility (including rail) at a European scale, starting with Keeble, Owens and Thompson (1982) and ESPON (2015: 46-55) offering a comprehensive overview. Many of these studies date back to the 1990s where the first phase of HSR construction and the fall of the iron curtain triggered an initial wave of research, but they offer a prognostic perspective only as it was still too early to measure accessibility effects. Many of these studies are now outdated or in need of evaluation.

Regarding the general distribution of rail accessibility, most studies confirm the well-established "blue banana" (Brunet 1989) pattern of an arch of high population density in North-Western Europe with the highest accessibility of the population (e.g. Poelman and Ackermans 2016). Results for multimodal accessibility similarly often find Paris and Frankfurt to be the centres of accessibility in Europe for longer trips (BAK Basel Economics AG 2007: 16). Martín and Reggiani (2007: 558) estimate dynamics of rail accessibility and describe a shift of the centre of gravity within the EU from Paris eastwards in the decade between 2007 and 2020. Peripheral regions on the Iberian Peninsula are often identified to be least accessible by rail. However, there are also situations that can be described as 'inner peripheries' and 'outer cores': some (mostly rural) regions that are geographically central within Europe are much less accessible than the agglomerations (Spiekermann and Neubauer 2002: 26), while on the other hand, agglomerations, typically the capitals, in countries that are geographically peripheral within Europe can nevertheless exhibit a high level of rail accessibility (Lutter, Pütz and

[2] Using the tool www.connectedpapers.com

Spangenberg 1993). Compared to road, rail accessibility is much more concentrated and discontinuous, but infrastructure investments can have a stronger influence on the distribution (Spiekermann and Wegener 2006: 16).

The scientific debate on whether HSR increases or decreases accessibility disparities between regions has been inconclusive. Depending on the chosen indicators, the network boundaries, and the data used, differing results have been obtained. On the one hand, several studies associate HSR with an increasing "polarisation" of accessibility and hence economic discrepancies or at least new layers of advantages and disadvantages on a European (Spiekermann and Wegener 1996: 38) and national scale (Plassard 1994: 61). High construction and running costs mean that HSR is usually first implemented between the most populous and economically dynamic regions, improving their connection and mutual accessibility, but not that of the area in between ("tunnel effect"). Such an increasing disparity is not necessarily accompanied by lower absolute accessibility levels in remote regions. Transport infrastructure and services in remote regions can be unchanged, or even slightly improved, and their absolute accessibility levels increased, but in relative terms their accessibility decreases compared to the central regions with even higher accessibility gains (Schliebe 1983; Spiekermann and Wegener 1996) in what Hall (2009: 65) called the "peripheralization of the periphery". Hence, selective accessibility gains lead to relative accessibility losses in most places (Martínez Sánchez-Mateos and Givoni 2009). However, there is also the risk of an absolute reduction of accessibility, particularly for smaller regional centres, if conventional rail services are discontinued after the opening of parallel HSR lines (Vickerman 1997: 26; Bruinsma and Rietveld 1993: 934).

On the other hand, several authors highlight a balancing effect of HSR on accessibility. Using average travel times to a number of chief economic activity centres weighted by GDP, Gutiérrez, González and Gómez (1996) find that the greatest increases in relative accessibility within the EU can be registered in regions in which (foreseeably) the stations of the future network will be located, but the greatest accessibility increases in absolute terms will correspond to the peripheral regions. They highlight that HSR also has an important symbolic dimension for cohesion. Lutter and Pütz (1993) assume strong changes of regional attractiveness through HSR, particularly for peripheral regions with an existing economic base, and plead for a European transport policy that seeks homogenous infrastructure provision across regions. Several more recent studies on a national level have likewise found beneficial effects of HSR for cohesion of accessibility (Gutierrez 2001; Monzon, Lopez and Ortega 2019).

There have been few studies specifically on regional rail accessibility in Germany. Evangelinos, Hesse and Püschel (2011) calculated a combined rail accessibility indicator for Germany consisting of gravitational accessibility of economic output, daily accessibility of population within four hours, and relative network efficiency. The studies find that Frankfurt by far dominates the ranking before Düsseldorf, Hannover, and Köln with Trier placing last. Regarding accessibility dynamics, Steinbach and Zumkeller (1992) projected that HSR expansion leads to the creation of a continuous zone of equally high rail accessibility throughout south-west Germany. Schliebe and Würdemann (1990) estimated an average rail travel time reduction between German regions of 45 minutes between 1990 and 2000. Using a contour-based travel time model without distance decay, they estimate that a high number of region pairs will fall within the critical four-hour threshold for daily return business trips. Beneficiaries are particularly the (then capital) city of Bonn and the West in general, while they do not predict large increases for Berlin. This study does not yet take into account the transport projects implemented after German reunification. Holzhauser and Steinbach (2000) close this gap and simulate the accessibility effects of the post-reunification transport projects and conclude that the economic cores of Eastern Germany (particularly Saxony, Saxony-Anhalt and Thuringia) will profit most, thereby balancing accessibility across the country's regions. In addition, they highlighted that Berlin would be released from its relative peripheral position.

The review shows that a high number of articles has been published in the decade between 1990 and 2000, when HSR was still very new and the end of the east-west conflict led to increased scientific interest in the reconstruction of a European transport network. However, many of the studies were in fact prognoses and no monitoring or updating has taken place.

1.4.2. Consequences of HSR Accessibility Changes at an Inter-regional Perspective

As the focus of this dissertation is on the local scale, studies using regions as base units can only briefly be reviewed here.

Several studies attribute a regionally balancing effect, and thereby the possibility to positively influencing economic development in lagging regions, to HSR (Sasaki, Ohashi and Ando 1997; Chen and Haynes 2017; Ahlfeldt and Feddersen 2018). For example, Ahlfeldt and Feddersen (2018) show, for the districts around the stations Montabaur and Limburg, a permanent increase in GDP in regions newly connected to the HSR network compared to control groups using a difference-in-differences approach. The increase is attributable not to relocations, but to productivity gains in companies that are already established through mechanisms of increased agglomeration economies. Chen and Vickerman (2017) and Cheng, Loo and Vickerman (2015) argue that impacts of rail accessibility on convergence is more accentuated for economically already more developed regions and continents. They conclude that in North-West Europe, HSR can be associated with convergence between and within connected regions, whereas in China it has contributed to specialisation.

At the same time, most studies find the effects to be only weak (Sasaki, Ohashi and Ando 1997; Cheng, Loo and Vickerman 2015; Bonnafous 1987). In one of the first studies on the topic, for example, Bonnafous (1987: 135-136) analyses the first TGV ("Train à Grande Vitesse") line and states that firms from Lyon expanded on the Paris market after opening of HSR and not vice versa. At the same time, there are countervailing effects on the Lyon economy through a lower number of business or tourist stays due to the possibility of day-return trips from Paris.

Puga and Venables (1997) and Fujita and Mori (1996) highlight the influence of the network structure on regional disparities; in a hub-and-spoke network increasing disparities between the hub and the spokes are more likely than in a system with multilateral connections. This can also be exploited to strengthen deliberately certain regions to the detriment of others. For example, Albalate, Bel and Fageda (2012) argue that national transport policy in Spain has followed an inherent and deliberate strategy of "centralisation", i.e. "to organize a country's communication and transportation networks in such a way that they converge on its political capital". In order to reduce regional disparities HSR should hence follow a "fully mixed" network design model and allow intermodal changeovers at stations to spread accessibility benefits to a wider area (Vickerman 1997: 32; Martínez Sánchez-Mateos and Givoni 2009; Chen and Hall 2013; Arnone et al. 2016: 164).

Many authors highlight that, while effects may exist, the influence of other factors on regional disparities and development is stronger than those of transport infrastructure investments and transport policy (Crescenzi and Rodríguez-Pose 2008: 62; Banister and Berechman 2001: 217). "In a society where globally all places are easily accessible, transport no longer structures anything" (Plassard 1994: 63). Further accessibility improvements are subject to decreasing returns (Axhausen, Fröhlich and Tschopp 2006; Axhausen 2008: 6), particularly in Europe, where accessibility is already on a very high level. Nevertheless, transport accessibility is an important precondition without which other factors cannot fully rise to importance. In sum, none of the regional growth and development theories presented before is alone able to fully explain development outcomes.

1.4.3. Consequences of HSR Accessibility Changes in an Local Perspective

Studies on local urban development around HSR stations have shown mixed results so far. On the one hand, there are numerous cases of areas assigned for commercial and residential development around HSR stations that have remained unexploited. For example, business parks around peripheral stations in small and medium-sized cities along the first HSR lines in France were generally not successful, even when local stakeholders had keenly anticipated the arrival of HSR (Mannone 1997: 578; Facchinetti-Mannone 2006; Vickerman 2015; Beckerich, Benoit and Delaplace 2019). The ambitious mixed-use new town project of "Valdeluz" near the Guadalajara-Yebes HSR station in Spain has been described as one of the largest real estate failures in the country paralysed by the economic crisis after 2008 (Bellet 2016: 53). Studies of land value changes as indicators for locational attractiveness have found only weak effects of intercity rail projects as compared to inner-city rail projects in the case of Berlin, Germany (Ahlfeldt 2012) and Taiwan (Andersson, Shyr and Fu 2010). Rather, public transport stations can also generate negative externalities such as noise, crime, or the risk of accidents, which can become reflected in depressed land values (Bowes and Ihlanfeldt 2001; Gargiulo and de Ciutiis 2010; Chang et al. 2014).

On the other hand, several studies find evidence for a positive relationship between HSR accessibility and urban development and see HSR stations as a "tool" for urban planning (de Ureña, Menerault and Garmendia 2009: 269). For example, Bellet, Pilar and Gutiérrez (2016: 193) conclude that the introduction of HSR can be an efficient instrument for urban development and one that has been capable of transforming the physical structure of cities, having analysed local planning responses to new HSR infrastructure in Spanish municipalities. Similarly, Garmendia et al. (2008: 257) find that the HSR station, together with the presence of a university, was able to redirect the residential growth of smaller cities along the first Spanish HSR line. In a case study of the new urban sub-centre station of Kassel-Wilhelmshöhe in Germany, Schütz (1997) finds evidence for urban intensification in a 5-10 minutes walking area around the station. Consequentially, he recommends integrating rail and real estate development (p. 158) and conceptually exploiting HSR connections to close building gaps around stations deliberately (p. 114), but also highlights the danger of generating sprawl at peripheral locations (p. 100). The developments around the stations of Montabaur, Erfurt, and Frankfurt Airport in Germany are regarded as successful cases of urban and economic development promotion by their stakeholders, and their accessibility advantages are often highlighted (Stadt Montabaur 2020; Landesentwicklungsgesellschaft Thüringen 2019; The Squaire 2020).

Several studies analysed the effects of HSR on commuting and suburbanisation. In Spain, the railway company offers specific commuter and suburban trains on their HSR network (Martínez Sánchez-Mateos and Givoni 2009; Moyano 2016), as this has shown to be unexpectedly profitable, particularly in the Madrid area, with the effect of spurring suburbanisation (Garmendia et al. 2008: 250; Mignerey 2013: 47; Guirao, Lara-Galera and Campa 2017; Guirao, Casado-Sanz and Campa 2018). HSR then acts as an accelerated means of regional mass transport. Particularly in spatial situations that involve one major metropolis, the monocentric model seems to be applicable. Demuth (2004) found an increased demand in the towns of Montabaur and Limburg on the German Frankfurt-Cologne route as a residential location for out-commuters. Heuermann and Schmieder (2018) determine that a 1% reduction in HSR train travel time increases the number of commuters between cities by 0.25%. Interestingly, they find that this effect is predominantly driven by out-commuters from larger to smaller cities. On the contrary, Hall (2009) notes that the fare structure of HSR often discourages commuting, such as in France.

At stations in central locations relative to the city they serve, development seems to be predominantly residential (Bellet, Pilar and Gutiérrez 2016: 170; Cervero and Bernick 1996) and business-oriented, while peripheral stations seem to be more attractive for industrial uses (Coronado, Ureña and Miralles 2019: 438; Beckerich, Benoit and Delaplace 2019: 574).

However, almost all authors agree that potential effects are neither automatic nor universal (Chen and Hall 2011: 689; Lutter and Pütz 1993: 619; Vickerman 1987: 188; BBSR 2019: 99-101). Their materialisation depends on the characteristics of the specific HSR project and further local influencing factors. HSR could enable and catalyse urban development, but it is never the sole determining factor (Bonnafous 1987: 136; Plassard 1994: 38; Givoni 2006: 605; Bellet, Pilar and Gutiérrez 2016: 164) – "conveyed" locational factors through transport infrastructure need complementary locally "bound" factors (Steinbach and Zumkeller 1992: 2).

1.4.4. Factors conductive to urban development

A review of previous academic and "grey" literature on urban development around HSR stations reveals a list of potential influencing factors presented in Table 1-2. Seven factors were identified that can be influenced by planning. Particularly, the embeddedness of a station in the urban context appears to be the most important planning factor for subsequent development followed by (local/regional) public transit connectivity. Loukaitou-Sideris and Peters (2020: 436) identify similar factors and group them into the three types: operational, intermodal, and spatial connectivity. In addition, there are factors beyond the scope of planners and policymakers, among them, the position of the city in relation to other cities and the metropolitan context and its economic endowments and trajectory.

	Factor	Authors
Factors influenced by planning	Station location close to urban centre, urban 'embeddedness'	Adolphson and Fröidh (2019: 8); Beckerich, Benoit and Delaplace (2019: 574 [agglomeration/urbanisation economies]); Coronado, Ureña and Miralles (2019: 438); Delaplace (2012: 278); Facchinetti-Mannone (2019: 461); Kim, Sultana and Weber (2018: 135); Loukaitou-Sideris et al. (2012: 63-65); Loukaitou-Sideris et al. (2013: 630); Loukaitou-Sideris and Peters (2020: 436); de Meer, Ribalaygua and Elena (2012: 205); Mignerey (2013: 39-40 [urban fringe location]); Mohino, Loukaitou-Sideris and Urena (2014: 328-331); Mohíno, Delaplace and de Ureña (2019: 174 [peripheral location better for small cities close to metropolitan centers]); Shen, de Abreu e Silva and Martínez (2014); Yin, Bertolini and Duan (2015: 27)
	Integration with conventional rail, local/regional public transport, Intermodality	Banister and Givoni (2013: 329); Beckerich, Benoit and Delaplace (2019: 574); Loukaitou-Sideris et al. (2012: 63-65); Loukaitou-Sideris et al. (2013: 630); Loukaitou-Sideris and Peters (2020: 436); Mannone (1997: 88); Marti-Henneberg (2015: 131); Mignerey (2013: 39-40); Mohino, Loukaitou-Sideris and Urena (2014: 328-331); Mohíno, Delaplace and de Ureña (2019: 175); Plassard (1994: 64); Preston and Wall (2008: 407); Sands (1993: 13-16, 22); Vickerman (1997: 34; 2015: 163); Yin, Bertolini and Duan (2015: 27)
	Quality of HSR service (frequency and type of services, attractiveness of destinations)	Eck (2000: 161 [travel time to hub airports]); Loukaitou-Sideris et al. (2012: 63-65); Loukaitou-Sideris et al. (2013: 630); Loukaitou-Sideris and Peters (2020: 436); Mannone (1997: 88); Moyano and Dobruszkes (2017); Mohíno, Delaplace and de Ureña (2019: 168)
	Planning, political intent, mobilisation of local stakeholders	Beckerich, Benoit and Delaplace (2019: 574); Bellet, Pilar and Gutiérrez (2016: 189); Delaplace (2012: 284 [new actor networks]); Facchinetti-Mannone (2006: 8; 2019: 461); Feliu (2012: 295); Givoni (2006: 605); Loukaitou-Sideris et al. (2012: 63-65); Loukaitou-Sideris et al. (2013: 630 [esp. additional public sector investment]); Loukaitou-Sideris and Peters (2020: 436); Mannone (1997: 86-89 [intercommunal cooperation]); Mignerey (2013: 39-40 [mobilisation, complementary planning, functional mix]); Mohino, Loukaitou-Sideris and Urena (2014: 328-331); Pol (2002 [vision and leadership]); Preston and Wall (2008: 420); Ribalaygua and Perez-Del-Caño (2019: 611-612); Vickerman (1997: 35 [complementary investment]; 2015: 164)
	Pedestrian access, walkability	Loukaitou-Sideris et al. (2013: 630); Loukaitou-Sideris and Peters (2020: 436); Otsuka et al. (2019)
	Station architecture and urban design	Loukaitou-Sideris et al. (2013: 630); Loukaitou-Sideris and Peters (2020: 436); Mohino, Loukaitou-Sideris and Urena (2014: 329 [barrier effects of tracks]); Trip (2008a; 2008b: 79-82); Wenner (2020)
	Availability of building land	Banister and Givoni (2013: 331); Beckerich, Benoit and Delaplace (2019: 589); Mannone (1997: 83); de Meer, Ribalaygua and Elena (2012: 205); Mohino, Loukaitou-Sideris and Urena (2014: 328-331); Schütz (1997: 150)
Other local factors	Location of the city related to other cities and in the metropolitan context	Coronado, Ureña and Miralles (2019: 447 [small cities in medium-sized metro areas]); Garmendia et al. (2012); Mohino, Loukaitou-Sideris and Urena (2014: 328-331 [proximity to metropolitan centre for sub-centre generation]); Ureña et al. (2012)
	Size of city, pre-existing economic composition and trajectory	Chen and Hall (2012); Coronado, Ureña and Miralles (2019: 444); Facchinetti-Mannone (2019: 461); Feliu (2012: 299 [postindustrial cities have higher pressure to act]); Garmendia et al. (2008: 249 [Presence of a university]); Mohíno, Delaplace and de Ureña (2019: 168 [city size]); Pol (2002; 2008 [service-oriented cities better prepared than post-industrial cities]); Steinbach and Zumkeller (1992: 2-4 ["locally bound" locational factors]); de Ureña, Menerault and Garmendia (2009); de Ureña et al. (2012); Vickerman (2015: 163); Yin, Bertolini and Duan (2015: 27)

***Table 1-2**: Factors influencing urban development around HSR stations (author)*

Several of the factors mentioned, particularly the station location or urban embeddedness, are common conflict issues between local actors on the one hand and those with a national and network-based purview on the other, in the context of smaller and medium-sized cities (Bellet 2016: 45; Facchinetti-Mannone 2006: 3; Zembri 1993: 286).

Factors that are less frequently discussed in literature encompass the influence of business cycles, image effects, and car access. The role of business cycles becomes particularly clear in the special case of the real estate crisis in Spain after 2008, which has brought several urban development projects close to HSR stations to a halt (Bellet 2016: 53; Bellet and Santos Ganges 2016: 15; Ribalaygua, Sánchez and de Ureña 2020: 458). It can even be argued that the enormous expansion of HSR in Spain itself followed the logic of the construction boom before. Image effects are described as both a consequence of the connection of a city to the HSR network and a separate reason for firm (re)locations (van den Berg and Pol 1998; Pol 2002; Willigers and van Wee 2011: 753). In fact, stated preference surveys often reveal that actual usage of HSR is low among firms that consider station proximity important, and find that image effects can outweigh the accessibility effects for location decisions of firms (Delaplace 2012: 282; Eck 2000: 149-153). Similarly, for many firms, car accessibility seems to trump public transport accessibility (Beckerich, Benoit and Delaplace 2019: 588; Demuth 2004: 124; van den Berg and Pol 1998: 496; Wulfhorst 2003: 120-121) and HSR stations are often coincidentally locations with good reachability by car.

Several authors also highlight the existence of a significant time-lag (Beckerich, Benoit and Delaplace 2019: 589) between opening of a station and urban development in its environs with estimates ranging from 5-7 years (Bonnafous 1987: 131) to more than 20 years (Bellet, Pilar and Gutiérrez 2016: 187). On the other hand, authors highlight the existence of (speculative) foreshadowing effects, particularly with respect to land prices, after the announcement of the construction of a new line but before its opening (Demuth 2004: 142; Ribalaygua, Sánchez and de Ureña 2020; Schürmann and Spiekermann 2011: 36). Figure 1-8 presents a sketch that summarises the results of this literature review. Unlike in a system model (Vester 2002: 239-254), however, the impact sketch does not attempt to attribute a passive influence to every component, as some relations are considered to be exogenous, and impacts cannot always be read as “the more … the more”.

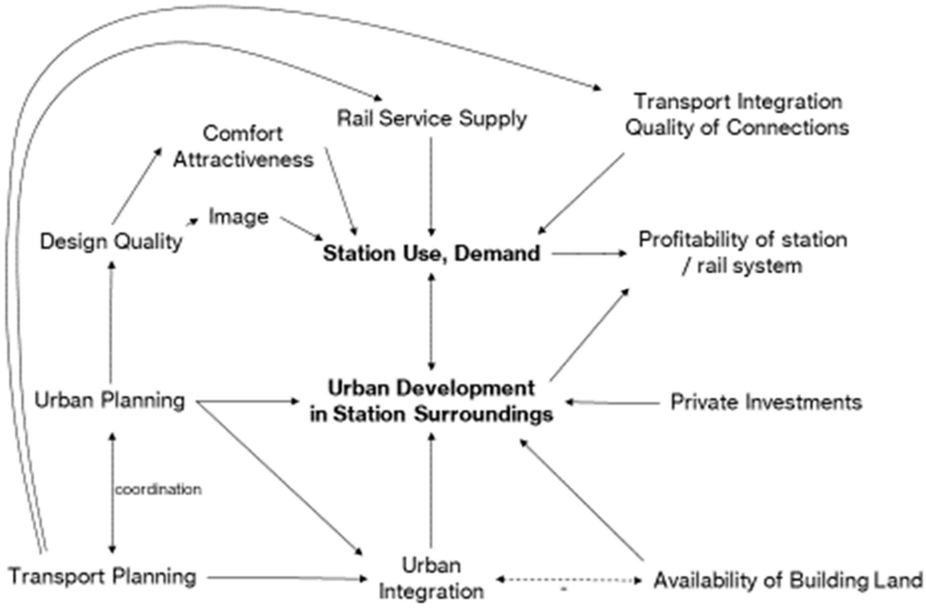

***Figure 1-8**: Impact sketch of factors influencing urban development around HSR stations. Dashed lines represent negative relationships (author)*

Most studies so far analyse a single case or line. Methodologically, there is a focus on qualitative and descriptive studies emphasizing local specificities. Quantitative-comparative, ex-post and long-term studies across a larger number of cases and entire networks are scarce (Coronado, Ureña and Miralles 2019: 435; Garmendia, Ribalaygua and de Ureña 2012: 30) with the notable exception of several recent studies with a geographical focus on Spain (Coronado, Ureña and Miralles 2019; Mohino, Loukaitou-Sideris and Urena 2014; Mohíno, de Ureña and Solís 2016; Ribalaygua, Sánchez and de Ureña 2020). Also, more studies cover the regional than the local scale.

1.4.5. Research Gaps

The literature review has revealed several research gaps with respect to the interrelations of HSR infrastructure and urban development. These encompass particularly:

- Studies on the accessibility changes induced by HSR infrastructure stem mostly from the early 1990s were often prognostic rather than analytic in nature, and require a review and update with current data. New data sources that were not available at the time, particularly digitalised timetables, allow more detailed and precise analyses and a comparison of ex-ante and ex-post analyses.
- There is a lack of both HSR accessibility analyses and analyses of the consequences of HSR accessibility changes for Germany. A large part of the recently published scientific studies focus on China, which provides ample case studies, but whose demographic, economic, and political conditions merit a separate treatment; and on Spain, the country with the second longest HSR network. The incremental, mixed-mode, and polycentric implementation of HSR in Germany has potentially contributed to the muted interest, as accessibility differentials are less stark. However, precisely these conditions, it can be argued, merit a detailed separate analysis.

- There is a wealth of individual case studies of single stations or lines but a lack of international comparative studies. While the individual circumstances of cases remain important, a more systematic comparison could uncover hidden patterns and complement case-related studies.
- The nature of urban development effects around new HSR stations is still highly disputed. The continued use of local and regional economic effects as an argument in the political discourse and the expected continued high future investments in HSR require that these relationships receive more attention in science.
- There is a scarcity of studies using fine-grained localised data or focusing on morphological and land use changes. At the same time, many studies of local effects rely on stated preferences, while new sources, such as on long-term land cover changes, allow the use of revealed preferences methods.

1.5. Research Objectives and Hypotheses

From the literature review and the research gaps follow the research objectives and hypotheses of this dissertation. The research objectives of the dissertation are threefold:

- to quantify and spatialise changes in accessibility through HSR,
- to analyse associated urban development processes, and
- to establish policy recommendations for sustainable and integrated urban and transport planning near HSR stations.

The spatial focus of the research is on Europe, especially on Germany.

Regarding accessibility changes, the dissertation hypothesises that HSR has indeed strongly influenced passenger rail accessibility in Germany in the last decades and continues to do so. Unlike in other European countries, however, the accessibility effects have been more regionally balanced, due to the chosen network design and service pattern. Regarding urban development outcomes, the hypothesis is that HSR can be associated with land use changes in the station surroundings, but only subject to certain preconditions, particularly, urban embeddedness, local and regional transport connections and the political strategy of local municipalities. A combination of local agglomeration and transport-related network externalities is assumed to support urban development. Figure 1-9 integrates and visualises the urban development hypotheses as well as the main relationships identified in the theoretical and literature review. It follows that HSR station planning should consider these conditions, in order to support sustainable development.

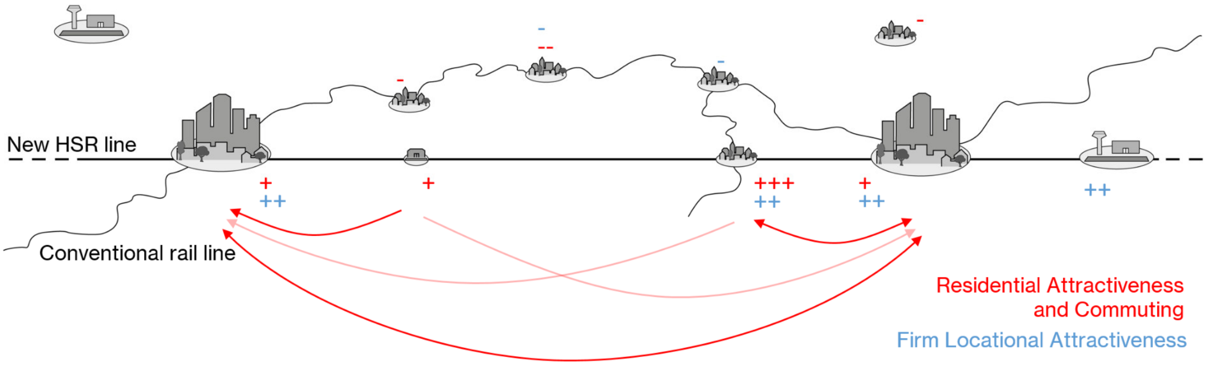

Figure 1-9: *Spatial impact sketch for new HSR line. Transparent lines represent weaker relationships (author)*

Due to the breadth of the topic, it seems important to highlight briefly, what the dissertation does *not* focus on. On the one hand, it leaves out questions of railway engineering, particularly those related to the technical construction of the line, and the specifications of the rolling stock, since this would lead too far away from the core question of land use-transport interactions. On the other hand, it does not cover questions of mode share, passenger growth, and line usage, since these topics have received substantial attention in literature already (e.g. Albalate, Bel and Fageda 2015: 171; Dobruszkes 2011).

1.6. Structure

The dissertation is structured into five chapters, which are concerned with different aspects of the research questions detailed before. Depending on the question, they focus on a different spatial scale and scope. Table 1-3 provides an overview of the chapters of this dissertation, which have also been published or submitted as journal articles or book chapters.

No.	Chapter Title	Research Question	Spatial Units	Spatial Extent
2	High-Speed Rail Accessibility in Germany: Changing Regional Disparities between 1990 and 2020	To quantify and spatialise changes in accessibility through HSR in the past	Regions	Germany
3	Which Regions Benefit from New Rail Accessibility? Germany in 2030	To quantify and spatialise expected changes in accessibility through HSR in the future	Regions	Germany
4	High Speed Rail as Urban Generator? An Analysis of Land Use Change around Stations in Europe	To analyse associated urban development processes	Station Surroundings	Europe
5	Euro-Star-Architecture: Comparing high-speed rail stations in Europe	To analyse associated urban development processes	Stations	Europe
6	Inside Out - Recalibrating Munich Metropolitan Region	To establish policy recommendations for sustainable and integrated urban and transport planning near HSR stations	Station Surroundings	Munich Metropolitan Region

Table 1-3: *Structure of the dissertation (author)*

The first two chapters focus on Germany and the regional scale for an analysis of accessibility changes through HSR. The literature review has revealed that a detailed analysis for Germany represents a research gap. Hence, and due to reasons of personal acquaintance of the local situation of the researcher as well as data availability, Germany was chosen as spatial extent. The latter has also influenced the choice of regions as spatial base unit, together with the aspect that HSR is primarily an inter-regional travel mode. However, the results obtained can also be used on a local scale. The last three chapters concentrate on the station itself and its immediate surroundings, as this is the scale where urban development effects are most expected. To generate enough cases for a comparative view, the spatial extent was widened to include all EU/EEA countries and the UK. In the final chapter, the spatial extent is again reduced to a single metropolitan region, as a current major rail infrastructure project in the Munich Metropolitan Region allows a detailed conceptualisation of policy recommendations relevant to the overall theme of the dissertation.

1.7. Methods and Data

Due to the comprehensive and multi-scale research design of this research, a mix of methods from different backgrounds, rather than one single method, is employed in this dissertation. While chapters 2 through 4 are analytical in nature and are based on methods of accessibility modelling and land use analysis, chapters 5 and 6 are more normative, and borrow from concepts of integrated land use and transport planning. For the sake of brevity and clarity, this chapter concentrates on the main aspects of each method. Detailed explanations can be found in the respective chapters.

1.7.1. Measuring and visualisation of accessibility

Chapters 2 and 3 of this dissertation are concerned with the question of measuring changes in accessibility over time. Accessibility is a concept that links transport infrastructure and land use in one indicator that describes a spatially differentiated feature: the quantity and quality of opportunities that can be reached from a certain place, taking into account the varying spatial friction (Ingram 1971: 101) that must be overcome to reach them. It is hence highly useful for the intertwined fields of transport and urban planning. The classical definition is that of Hansen (1959: 73) where accessibility is “the potential of opportunities for interaction”. Both an improvement in transport infrastructure and a densification of “opportunities” can increase accessibility. The concept represents an application of “time-geographical” thinking (Hägerstrand 1970).

A range of methods has been developed to operationalise the accessibility concept in empirical studies. Often, population size, employment, or GDP is used as “opportunity” parameter. Different indicators have been applied to represent the transport component, mostly travel time, but also distance, generalised costs (including monetary costs) (e.g. Beria, Debernardi and Ferrara 2017) or, recently, emissions (Kinigadner 2020). In addition, a range of functions to model the spatial “friction” has been discussed, reaching from ‘simple’ cut-off-thresholds after a certain distance or time, to more complex functions applied to the transport component, such as power (Bruinsma and Rietveld 1993; Rich 1978), Gaussian (Ingram 1971) or “radiation” (Simini et al. 2012) functions (see Song (1996), Geurs and van Wee (2004) and Levinson and Wu (2020) for an overview).

Each specific accessibility indicator captures only some dimensions of the accessibility concept; hence, it is useful to combine several sub-indicators (Martín and Reggiani 2007: 555). Some studies of HSR use travel times to one specific selected destination without distance decay to measure accessibility changes (e.g. Martínez Sánchez-Mateos and Givoni 2009 to London in the case of the UK). This is problematic for polycentric spatial settings. Hence, to model friction, the dissertation employs on the one hand exponential ("gravitational") functions, as they are most common in transport research, have been found to match human behaviour closely (Song 1996: 479), and are tied to travel behaviour theory (Geurs and van Wee 2004: 133; Handy and Niemeier 1997: 1177). The research generally uses population as "opportunity" component since it represents a well available and neutral indicator compared to alternative destination weights. Population size of a destination region represents the number of potential business contacts, customers, and employees that can be reached there. For reasons of clarity and data availability, it also uses travel time as quality side of the transport network, even though most travellers typically consider a wider set of characteristics of the level of service before deciding on a travel option, which can however (partly) be subsumed therein (e.g. Ingram 1971: 102). On the other hand, graph theory is applied to transport network data to construct an indicator of degree centrality, i.e. the number of destinations – regions – reachable without a change of service, as second indicator.

The resulting indicator is dimensionless and not always easy to interpret. However, it allows relative comparisons across different localities. In addition, the indicator is calculated for several instances over time, which are visualised in relation to each other, which also facilitates intertemporal comparisons. The accessibility model used is monomodal for Germany and surrounding countries, and uses 266 functional urban areas as spatial base units.

1.7.2. Analysis of land cover data

Chapter 4 describes the results of an evaluation of land use changes around HSR stations in Europe using a database of 232 stations along newly constructed HSR lines since 1981. The station database contains information on the opening year, available services, distance to urban centres and other stations, available complementary local and regional public transport, among others. It was compiled manually based on a review of academic and "grey" literature, the study of aerial photographs, and online timetables. Stations were clustered into groups based on a typology developed in previous literature (Troin 1997).

The chapter analyses changes in land cover in the vicinity of the stations, in relation to the variables contained in the station database using CORINE land cover (CLC) data by the European Copernicus Programme (EEA 2019). CLC data is based on the evaluation of high spatial resolution satellite images assisted by topographic maps, orthophotos and ground survey data, it grades land uses into 44 classes, and is available for five points in time between 1990 and 2018. The results are analysed with the use of quantitative descriptive statistics. While the relatively coarse resolution of static CLC data has led to doubts on its utility for small-scale analyses (Siedentop and Meinel 2004: 8) the dynamic "change layer" has a much higher resolution. The analysis rests on the latter.

Generally, land use change as an indicator has been less frequently investigated than other indicators in studies of transport infrastructure expansions (Kasraian et al. 2016: 781, 788), and mostly for dynamics within city-regions. Hence, the analysis of inter-regional transport infrastructure on land cover change presents a research gap.

1.7.3. Node-place-modelling

Chapters 5 and 6 are concerned with the normative dimension of integrated land use and transport planning. Among the central aims of the current leitmotif of sustainable urban planning are the economical use of space, the reduction of emissions, and the incentivisation of socially mixed neighbourhoods. One approach to support these aims is transit-oriented development, i.e. the development and densification of land uses around stations of high-quality public transport, and vice versa – the adequate provision of such services in already densely built-up neighbourhoods. In other words, the density of activities around a public transport station should be in balance with the accessibility it provides.

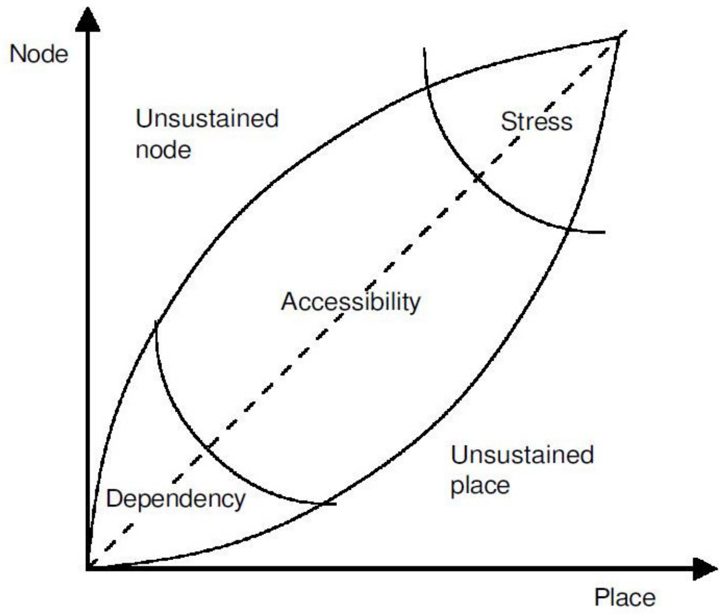

***Figure 1-10**: The node-place model (Bertolini 1999: 201)*

A conceptual model that describes this relationship is the "node-place-model" by (Bertolini 1999) (Figure 1-10) that proposes aiming for a balance of the two dimensions of "node" (accessibility) and "place" (functional density) at each station. It allows visual identification of "unsustained nodes" (stations with an accessibility surplus), "unsustained places" (with a surplus of functions), as well as "dependent" and "stressed" stations that are balanced but in danger of inefficiency or overcrowding. The model has been applied in numerous settings (e.g. Gilliard et al. 2017; Caset et al. 2019). It has also successfully been applied to HSR stations in Korea (Kim, Sultana and Weber 2018). In this dissertation, it is adapted for the case of HSR stations in Europe and station design, as well as applied to stations of the new express rail service in the Munich Metropolitan Region (MMR).

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2. Rail Accessibility in Germany: Changing Regional Disparities between 1990 and 2020

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Abstract: Transport accessibility is an important location factor for households and firms. In the last few decades, technological and social developments have contributed to a reinvigorated role of passenger transport. However, rail accessibility is unevenly distributed in space. The introduction of high-speed rail has furthermore promoted a polarisation of accessibility between metropolises and peripheral areas in some European countries. In this paper we analyse the development of rail accessibility at the regional level in Germany between 1990 and 2020 for 266 functional city-regions. Our results show two different facets: the number of regions that are directly connected to one another has decreased, but at the same time the spatial disparities of accessibility have decreased, albeit to a small extent. This development was strongest in East Germany after German reunification and thus largely a consequence of the renovation of the conventional rail infrastructure, not high-speed rail. Nevertheless, it can be concluded that the introduction of high-speed traffic in Germany did not lead to an increase in accessibility disparities. Instead, the accessibility effects of high-speed rail in Germany seem to break the traditional dichotomy between core and periphery.

Keywords: Accessibility, Rail, High Speed Rail, Regional Disparities, Germany

Contributions (CRediT taxonomy): Conceptualisation, F.W.; methodology, F.W.; validation, F.W., A.T.; formal analysis, F.W.; investigation, F.W.; data curation, F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W., A.T.; visualisation, F.W.; supervision, F.W., A.T.; project administration, F.W.

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2.1. Introduction

Accessibility is an important determinant of regional and local development (Clark 1958). Transport infrastructure and services expand the opportunities for households to access distant jobs and amenities, and support, inter alia, the emergence of agglomeration benefits for firms. Hence, accessible places and regions have long attracted economic activity (Axhausen 2008: 5).

After a phase of relative decline, passenger rail transport has experienced a resurgence as a transport mode in Europe during recent decades. Several societal and technological developments have contributed to this reinvigoration. Tertiarisation and the rise of the knowledge economy have increased demand for face-to-face communication and business travel (Hall and Pain 2006: 7; Thierstein et al. 2008). This has supported reurbanisation and a tendency towards polycentric development which involves the major metropolitan cores (Münter and Volgmann 2014) being increasingly organised in a global space of flows (Castells 1996). These processes are advantageous to passenger rail as a linear, mass-transport oriented form of transport, which furthermore often directly services inner-city areas and allows travel time to be used for work purposes. At the same time, rail infrastructure can reinforce this pattern towards "integrated corridor economies" (Blum, Haynes and Karlsson 1997: 1). Changing consumer preferences with regard to ecological concerns are also an advantage for rail as opposed to air and road travel due to its relatively low emissions (cf. Schwarzer and Treber 2013). Finally, there have been technological and managerial improvements, particularly in the form of high-speed rail which has greatly increased average speeds on some routes. This has improved the competitive advantage of passenger rail for many routes. Hence, passenger rail accessibility plays a growing role in locational decisions.

However, accessibility is unequally distributed in space, and the described developments have sometimes contributed to a widening of rail accessibility disparities between regions. Particularly, the introduction of high-speed rail has been discussed in scientific literature as promoting a polarisation of accessibility between metropolitan cores on the one hand and peripheral areas on the other, on a European scale and also within several European countries (Spiekermann and Wegener 1996). Its capital intensity and technical characteristics mean that high-speed rail is established first on routes between major metropolitan centres, while parallel, slower conventional services with more frequent stops are in some cases discontinued. At the same time, conversely, it has been argued that high-speed rail can serve cohesion goals when it links peripheral and central regions (Monzon, Lopez and Ortega 2019: 527). Likewise, recent decades have seen an increased profit orientation and the (partial) privatisation of several national rail providers throughout Europe with adverse consequences for regional accessibility in some countries, as peripheral and tangential lines often have the lowest internal profitability. On the other hand, progressing European integration has in some cases reduced the peripherality of border regions in the rail network.

Despite numerous (mostly ex-ante) studies in several European countries and for Europe as a whole, there have been few assessments of the development of rail accessibility in the case of Germany. During the last three decades, the rail network has been influenced by the triple effects of reunification, the de jure privatisation of the railway service provider, and the construction of more than 1,000 km of new high-speed rail infrastructure, which has reshuffled regional accessibility. Accessibility studies in countries with a monocentric urban structure and radial network development, such as France, Spain and the UK, have often found accessibility changes to be essentially a function of the reduction of travel time to the main metropolis. The polycentric spatial structure and dispersed network layout in Germany means that accessibility developments are expected to be less clear.

Furthermore, continuing digitalisation of previously analogous data means that new sources become available for use in research, such as historical timetables that allow an ex-post assessment of accessibility levels. The research presented by this paper exploits a novel source, a digitalised database of German long-distance rail timetables from 1987 until today.

The aim of the paper is to analyse and visualise the spatially differentiated development of rail accessibility among German regions during the last 30 years. We develop a monomodal rail accessibility model for 266 functional city-regions in Germany in 10-year intervals between 1990, the year prior to the introduction of high-speed rail in Germany, and 2020, using potential accessibility and degree centrality indicators. Our study links back to the considerable body of research on regional accessibility changes caused by European integration published during the 1990s, and re-examines their ex-ante projections and results against the background of longitudinal and current data gathered using novel methods and sources. The main research question is: Has the spatial distribution of passenger rail accessibility in Germany become more equitable during this time period?

The paper is structured as follows. In the subsequent second section, we briefly revisit previous rail accessibility analyses in Europe before we provide more detail of our case study in Section 3. The fourth section describes the methods and data used. In the fifth section, we present results before concluding with more general remarks and implications in the sixth section.

2.2. Rail accessibility disparities and dynamics in Europe

Rail accessibility changes can be analysed on different spatial scales, from the station surroundings to the regional (Mohino, Loukaitou-Sideris and Urena 2014) and national scales. This paper is focused on the regional scale, as we are interested in the effects of inter-regional infrastructure and service changes, even though accessibility changes on the local level can be substantial as well, particularly in the case of line closures, which merits a separate discussion. We hence conceptualise these regions as 'containers' which are uniformly affected by an accessibility change.

There is a rich literature on regional accessibility (including rail) on a European scale, starting with Keeble, Owens and Thompson (1982). ESPON (2015: 46–55) offers a comprehensive overview. Many of these studies date back to the 1990s, where the first phase of high-speed rail construction and the fall of the iron curtain triggered an initial wave of research, and are static. As it was still too early to measure accessibility effects, many of these studies are now outdated, or only present forecasts but no evaluation.

Regarding the general distribution of rail accessibility, most studies confirm the well-established 'blue banana' (Brunet 1989) pattern of an arch of high population density in north-western Europe with the highest accessibility of population (e.g. Poelman and Ackermans 2016). Results for multimodal accessibility similarly often find Paris and Frankfurt to be the centres of accessibility in Europe for longer trips, and for continental and global accessibility (BAK Basel Economics 2007: 16). Martín and Reggiani (2007: 558) estimate dynamics of rail accessibility and describe a shift in the centre of gravity within the EU from Paris eastwards in the decade between 2007 and 2020. Peripheral regions on the Iberian Peninsula are often identified as being least accessible by rail. However, there are also situations we call 'inner peripheries' and 'outer cores': some (mostly rural) regions that are geographically central within Europe are much less accessible than the agglomerations (Spiekermann and Neubauer 2002: 26). On the other hand, agglomerations, typically the capitals, in countries that are geographically peripheral within Europe can nevertheless exhibit a high level of rail accessibility (Lutter, Pütz and Spangenberg 1993). Compared to road, rail accessibility is much more concentrated and discontinuous, but infrastructure investments can have a stronger influence on the distribution (Spiekermann and Wegener 2006: 16).

The dynamics of rail accessibility have been studied particularly under the lenses of European integration and high-speed rail development. High-speed rail is commonly defined as newly built lines for speeds of 250 km/h or more, and upgraded lines for at least 200 km/h (European Council 1996); speeds in Europe reach 320 km/h. First developed in Japan with the Shinkansen in 1964, high-speed rail has been introduced in and between a number of European countries, including Italy (1977), France (1981), Germany (1991) and Spain (1992). International high-speed rail corridors within the EU only materialised at a late stage, mainly as part of the Trans-European Networks (TEN) programme, and essentially involved stitching together the national networks (Vickerman 1997: 22). Network length and ridership have since grown strongly[3] and new lines continue to be proposed and built. Resulting travel time changes have been very dynamic and are typically more sudden and stronger than for other modes (Bruinsma and Rietveld 1998: 518; BAK Basel Economics 2007: 16). This is advantageous for scientific analysis, since the identification and association of effects becomes more difficult in situations with gradual changes.

High-speed rail networks were essentially developed nationally by the (state-owned) railway companies and vary e.g. with respect to network structure, intermodality and station placement, which can all have a decisive influence on accessibility outcomes. Monocentric and politically centralised countries typically exhibit a network structure more radially aligned to their capitals (cf. Albalate, Bel and Fageda 2012). Systems range from fully segregated separate high-speed rail infrastructure to full integration between conventional, high-speed rail and even freight traffic (Campos and de Rus 2009). Integrated systems are typically more expensive, but allow a better trickling-down of accessibility effects. There are also differences regarding station placement and service provision. While the capital intensity and technical

[3] http://www.uic.org/spip.php?action=telecharger&arg=102 (15.12.2020).

characteristics of high-speed rail typically mean that it is first implemented between major centres over the shortest possible distance, some lines include (out-of-town) stations in peripheral and rural areas that happen to be located on such axes, greatly increasing their accessibility. On the other hand, there is the risk of a reduction of accessibility, particularly for smaller regional centres, if conventional rail services are discontinued after the opening of parallel high-speed rail lines (Bruinsma and Rietveld 1993: 934; Vickerman 1997: 26).

Spain now has the longest high-speed rail network in the world after China, both of which have attracted substantial academic interest (e.g. Cao et al. 2013; Monzon, Lopez and Ortega 2019; Ribalaygua and Perez-Del-Caño 2019). The scientific debate on the question of whether high-speed rail increases or decreases accessibility disparities between regions has been inconclusive. On the one hand, several studies associate high-speed rail with an increasing 'polarisation' of accessibility and hence economic discrepancies or at least new layers of advantages and disadvantages on a European (Spiekermann and Wegener 1996: 38) and national scale (Plassard 1994: 61). High construction and running costs mean that high-speed rail is usually first implemented between the most populous and economically dynamic regions, improving their connections and mutual accessibility, but not that of the area in between ('tunnel effect'). Such an increasing disparity is not necessarily accompanied by lower absolute accessibility levels in remote regions. Transport infrastructure and services in remote regions can be unchanged, or even slightly improved and their absolute accessibility levels increased, but in relative terms their accessibility decreases compared to the central regions where accessibility gains are even higher (Schliebe 1983; Spiekermann and Wegener 1996); Hall (2009: 65) called this the "peripheralization of the periphery".

On the other hand, several authors highlight the balancing effect of high-speed rail. Using average travel times to a number of chief economic activity centres weighted by GDP, Gutiérrez, González and Gómez (1996) find that the greatest increases in relative accessibility within the EU can be registered in regions in which (foreseeably) the stations of the future network will be located, but the greatest accessibility increases in absolute terms correspond to the peripheral regions. They highlight that high-speed rail also has an important symbolic dimension for cohesion. Lutter and Pütz (1993) assume strong changes of regional attractiveness through high-speed rail, particularly for peripheral regions with an existing economic base, and plead for a European transport policy that seeks homogenous infrastructure provision across regions. Several more recent studies on a national level have likewise found beneficial effects of high-speed rail for the evenness of accessibility (Gutierrez 2001; Monzon, Lopez and Ortega 2019). Nevertheless, the economic effects even of an accessibility increase for peripheral regions are contested, a "straw effect" could mean that they lose economic activity to the core regions (Ottaviano 2008: 19). In any case, such effects are context-specific and far from automatic (Chen and Hall 2011). Many authors highlight that for high-speed rail to reduce regional disparities, mixed-mode services combining high-speed and conventional stretches and intermodality at high-speed rail stations are important for spreading accessibility benefits to a wider area (Vickerman 1997: 32; Martínez Sánchez-Mateos and Givoni 2012; Chen and Hall 2013).

The review shows that there is a need for more analyses on the dynamics of accessibility disparities. Many of the recent studies specifically treat a selected single line, while systematic studies across cases are rare. Several authors call for greater attention to be paid to comparative, quantitative accessibility analyses over a longer time frame (Levinson and Wu 2020: 149) and between different states of networks (Axhausen 2008: 20; BBSR 2019: 103), and demand continuous accessibility modelling (Stępniak and Rosik 2018: 309).

2.3. **Case Study: Germany**

The development of railway infrastructure and services in Germany has been characterised by three broad trends during recent decades: high-speed rail construction, privatisation and the aftermath of German reunification.

The construction of several new high-speed rail lines in West Germany started in the 1970s, after a long phase of little investment in rail infrastructure. The conventional rail network in Germany was considered outmoded and unfit fur purpose (Schliebe 1983), also because the traditionally strong east-west routes were severed. Construction followed a demand-driven rationale, mostly in north-south orientation, as despite the strong growth of car and lorry traffic some lines were operating at their capacity limit (Schliebe and Würdemann 1990: 227-229). In contrast to other European countries, the new lines were designed for freight train use as well, to connect the southern industrial regions with the harbours in the north. This required gentler slopes and hence expensive tunnelling and bridging in the hilly terrain of central Germany, which significantly increased costs and landscape encroachment (Jänsch 1991: 367). Planners also aimed for interoperability between conventional and high-speed rail, i.e. high-speed trains also use conventional lines, and conventional intercity trains and even regional trains use stretches of the high-speed network, a "fully mixed" network mode (Campos and de Rus 2009: 20-21). After the opening of the first high-speed rail line in Germany between Hannover and Würzburg in 1991, the 'Inter-City Express' (ICE) brand was introduced for high-speed trains. The ICE soon reached the expected passenger volumes and profitability (Jänsch 1991). To date, seven high-speed rail lines covering 1260 km have been completed.

The privatisation of railways has had an effect on rail services in recent decades throughout Europe. The UK went furthest with the full privatisation of rail operations in 1994, including the network infrastructure. Other European countries re-organised and sometimes semi-privatised their mostly still national rail companies, initiated by EU legislation on equal access to infrastructure networks and a reform of the subsidy regime for transport provision. In general, many of the still national, integrated companies were separated into a network and a service operation company, and often further subdivided into freight and passenger rail. The German state railway company Deutsche Bundesbahn was transformed into a private enterprise (Deutsche Bahn, DB) in 1994, but with 100% of the shares in public ownership. Successive governments aimed for a (part-)divestment, but the plan was ultimately dropped in the 2008 financial crisis. Together with EU laws on public transport subsidies, the reorganisation meant the concentration of DB on profitable long-distance lines, while (inter)regional services were discontinued or left to be subsidised and competitively tendered by the federal states.

A special circumstance in the German case is the reunification of its eastern and western parts in 1990. Many connections across the inner-German border, particularly local lines, had been severed since the establishment of the two German states and were subsequently re-established in the years after 1990. The two separate railway companies were merged. In addition, a set of large-scale transport infrastructure projects, the "German Unification Transport Projects" (Verkehrsprojekte Deutsche Einheit, VDE) were set up to reconnect east and west and improve transport infrastructure in East Germany. They included nine rail projects, among them two new high-speed rail lines, at an investment volume of approximately 15 bn euros (Holzhauser and Steinbach 2000: 129).

Recently, there have been calls for Deutsche Bahn to refocus on its role as a domestic supply-oriented public service provider, rather than a profit-oriented internationally operating firm, particularly to be able to implement climate protection targets. Following the example of the Netherlands and Switzerland, rail policy is also increasingly oriented towards optimising seamless interchanges and adapting infrastructure to the desired 'integrated timetable', rather than vice versa. The most recent Federal Transport Infrastructure Plan (Bundesverkehrswegeplan) with a time horizon of 2030 allocates about 40% of new investment in transport infrastructure to rail projects and contains eight new passenger high-speed lines for 250 km/h or more, including those necessary for integrated timetables, the so-called Deutschland-Takt (BMVI 2016: 41).[4]

There have been few studies specifically on regional rail accessibility in Germany. Evangelinos, Hesse and Püschel (2011) calculated a combined rail accessibility indicator for Germany consisting of gravitational accessibility of economic output, daily accessibility of population within four hours and relative network efficiency. The research found that Frankfurt by far dominates the ranking, before Düsseldorf, Hannover and Köln; Trier being last. Regarding accessibility dynamics, Steinbach and Zumkeller (1992) projected that high-speed rail expansion would lead to the creation of a continuous zone of equally high rail accessibility throughout south-west Germany. Schliebe and Würdemann (1990: 233) estimated an average rail travel time reduction between German regions of 45 minutes between 1990 and 2000. Using a contour-based travel time model without distance decay, they estimated that a high number of region pairs would fall within the critical four-hour threshold for daily return business trips. Beneficiaries were particularly the (then capital) city of Bonn, and the West in general, while they were pessimistic for Berlin. This study did not take into account the VDE projects. Holzhauser and Steinbach (2000) closed this gap and simulated the accessibility effects of the post-reunification transport projects, concluding that the economic cores of eastern Germany (particularly Saxony, Saxony-Anhalt and Thuringia) would profit most, thereby balancing accessibility across the country's regions. In addition, they highlighted that Berlin would be released from its peripheral position.

[4] Also see https://www.bmvi.de/SharedDocs/DE/Artikel/E/zukunftsbuendnis-schiene.html (15.12.2020).

2.4. Methods

The aim of the empirical part of this paper is to estimate rail accessibility for business trips in Germany on a regional scale between 1990, the year before the opening of the first high-speed rail line, and today. Despite their often positive and significant relationships, "macro-level models" (Berechman 1995: 22), which use some measure of the capital stock (e.g. km of road) as an explanatory variable, fail to account for the fact that transport infrastructure investments are not made in isolation. The alignment and position in the network of such investments provide a vital context for their effects (Banister and Berechman 2001: 210; Axhausen, Fröhlich and Tschopp 2006: 3). Accessibility measures, which consider the actual services provided by infrastructure networks, are thus preferable.

Accessibility can be defined as the "potential for opportunities of interaction" (Hansen 1959: 73) of a territory or place and can be measured in various ways. Detailed overviews of the operationalisation of accessibility can be found in Song (1996), Geurs and van Wee (2004) and Levinson and Wu (2020). In this paper, we mainly use two accessibility measures: potential accessibility using an exponential decay function, and degree centrality. Each specific accessibility indicator captures only some dimensions of the accessibility concept; hence, it is useful to combine several sub-indicators (Martín and Reggiani 2007: 555). Potential accessibility shows the advantages that a rail connection provides in terms of proximate contact partners within a typical daily return travel journey, while degree centrality emphasises direct connectedness without changeovers, with no distance decay.

2.4.1. Potential Accessibility

Some studies of high-speed rail use before/after travel times to one specific selected population centre as a proxy for accessibility change (e.g. Martínez Sánchez-Mateos and Givoni 2009 to London in the case of the UK). This might be a permissible approximation in monocentric settings, but it cannot be applied in the German case. For polycentric situations, potential-based measures are more useful. Potential accessibility measures are calculated by summing up the number of destinations that can be reached from a point in a network, each weighted by its attractiveness (e.g. economic mass or population), and inversely weighted by distance. They rest on the assumption that the likelihood for personal interactions, and consequently travel, from location i to a certain destination j depends on the number of opportunities the destination presents, and the difficulty to reach it (Barthélemy 2011: 35). Potential measures have been widely used in human geography and transport studies and represent an adequate way to measure the benefits of transport projects, since they do not depend on assumptions concerning user benefits and include (wider) societal benefits (Beria, Debernardi and Ferrara 2017: 68). As the opportunity component of our analysis, we use population, since it represents an easily available and neutral indicator, compared to alternative destination weights such as GDP. Population size of a destination region represents the number of potential business contacts that can be reached there. To measure distance, we use travel time.

Different types of functions can be used to model the distance decay. Exponential functions – also called gravitational functions – are most often used and generally considered most suitable (Song 1996: 479) since they are closely tied to travel behaviour theory (Handy and Niemeier

1997: 1177; Geurs and van Wee 2004: 133) and match empirical observations well. For our study, we use an exponential decay function in the form of eq. 2-1,

$$P[i] = \sum_{j\ \in G-\{i\}} \frac{W[j]}{e^{\beta * d[i,j]}} \qquad \text{(eq. 2-1)}$$

where P[i] is the potential accessibility of location i, W[j] the weight of destination j, d[i,j] is the travel time between locations i and j, and β is the exponent for adjusting the distance decay.

The decay factor is scale-dependent and hence must be adjusted for each case study depending on the travel purpose and the demand characteristics, based on observed data or comparative cases from the literature (Frost and Spence 1995: 1834; Geertman and Ritsema van Eck 1995: 70; Geurs and van Wee 2004: 133). Higher values mean a stronger distance decay and are hence suitable for short-distance interactions with greater emphasis on the land use component. The necessity for consistent data across all timescales limits the spatial resolution of our analysis to the (inter)regional scale, which is adequate for business-purpose daily return trips. A wide variety of decay factors is used in the literature, an overview can be found in Rosik, Stępniak and Komornicki (2015: 140). Studies with a similar approach have used decay factors in a very wide range, from 0.5 (Poelman and Ackermans 2016), 0.2 (Axhausen, Fröhlich and Tschopp 2006) to 0.0051 (BAK Basel Economics 2007: 44) which represent a halving of the weighting after 1.3, 3.45 and 135 minutes, respectively. For this study, we follow the principle described by Östh, Reggiani and Galiazzo (2014) that the distance decay parameter should be fitted so as to match the halving of the weighting to the median travel time typical for the travel purpose under consideration. A range of international studies set the median travel time for business daily return trips at about two hours (e.g. Andersson and Karlsson 2004: 293; BAK Basel Economics 2007: 44 for meetings and trade fairs; Rosik, Stępniak and Komornicki 2015: 140 for ‘international’ trips). Recent statistical data for Germany on this issue is unavailable, but in line with these studies a decay factor of 0.0057 can be deduced from the distance-based values in Harrer and Scherr (2013: 65), assuming an average speed of 90 km/h and omitting very short-range trips.

A challenge of the potential indicator lies in its interpretability and communicability, as the resulting values are dimensionless and meaningful only in reference to other values, and hence should be normalised to make sense (Geurs and van Wee 2004: 134). Its value lies especially in comparisons over time, not in absolute terms. We hence normalise all values to the highest value in 2020 as 100. Particular attention must also be paid to the zone-internal travel time at the origin location, which is known as the ‘self-potential’ problem (Geertman and Ritsema van Eck 1995: 71; Bruinsma and Rietveld 1998: 503). Using the undiscounted mass of the origin would lead to an overestimation of the local mass. As an approximation, Frost and Spence (1995: 1835) suggest applying the distance decay factor to 0.33 times the radius of the origin area. For this paper, we follow the more precise method of Stępniak and Jacobs-Crisioni (2017) and calculate for each region the average weighted air-distance to the main station from each point of the 1x1 km GHSL population grid[5] for the last available year before each analysis year

[5] Global Human Settlement; see https://ghsl.jrc.ec.europa.eu/download.php?ds=pop (15.12.2020).

to correct for differing internal population distributions, for which the distance decay is applied as well. Lastly, the network boundaries must be chosen in a way that is relevant to the research question to avoid an underestimation of accessibility in border regions. We hence include a buffer zone of four hours travel in our analysis and do not apply a border penalty, since all neighbouring countries are now part of the Schengen zone and rail travel is mostly frictionless.

2.4.2. Degree centrality

Rather than the number of potential contacts that can be reached at a certain cost being decisive for the attractiveness of a region, it might be that the number of destinations that can be reached directly from a certain origin, regardless of the travel time required, is more important. For example, Florida (2017) highlights the importance for a city's economic development of the number of destinations that can be reached with a direct flight. Likewise, local stakeholders in the German case have argued that direct rail connections to important urban centres are preferable to short travel times that require changeovers (e.g. Seydack 2015). Changeovers induce uncertainty in a travel chain and pose a disadvantage particularly for occasional users. As a second accessibility measure, we hence determine the number of other regional centres that can be reached directly without changing trains from a regional centre. In graph theory, this measure is one of the most basic features of a graph and is called 'degree' (Barthélemy 2011: 6) or degree centrality. It was defined by Freeman (1979) and is based on the idea that important nodes have the largest number of adjacent nodes (Erath, Löchl and Axhausen 2009: 383). In spatial networks, it is usually limited by geography, but this applies to a lesser extent to rail services, which can use several successive physical lines. The analysis of degree centrality is limited to the German rail network without the buffer zone. Mathematically, degree centrality can be formulated as:

$$D[i] = \sum_{j \in G-\{i\}} A_{ij} \qquad \text{(eq. 2-2)}$$

where D[i] is the degree centrality of location i, and A_{ij} is defined as 1 if i and j are connected, 0 otherwise.

Our analysis covers four points in time: 1990, 2000, 2010 and 2020. We use dynamic population values as an 'opportunity' measure, which gives a more realistic impression of regional accessibility development, particularly given the long timespan of the analysis and the strong population shifts especially in eastern German regions since 1990. However, we perform an alternative calculation with constant population to isolate the effects of transport infrastructure changes on accessibility as opposed to population effects (cf. Stępniak and Rosik 2018). The dynamic population data used during the study period means that accessibility changes can be caused by both shorter travel times and changing population size. We hence calculate an alternative scenario with the rail network of 1990 but the population distribution of 2020, and subtract it from the actual calculation. The result allows the different factors influencing the accessibility growth to be discerned (cf. Condeço-Melhorado, Zofío and Christidis 2017).

2.4.3. Limitations of accessibility models

All accessibility indicators used here suffer from a number of limitations. First, the accessibility value of one node is attributed to the whole region. This generalisation can produce unrealistic results, as some parts of the region might be less accessible than the main city (Gutiérrez, González and Gómez 1996: 237). Using homogenous functionally defined regions can mitigate this shortcoming to a certain degree. Consequently, this means that inner-regional accessibility changes, e.g. through the closure of smaller local rail lines, are not covered by the analysis. However, such closures were widespread in the 1990s and 2000s, particularly in eastern Germany, and might have led to drastic accessibility losses on a finer scale. The meaningfulness of the model hence always depends on the adequate choice of nodes and zones (Bruinsma and Rietveld 1998: 502). Second, frequencies of connections are only implicitly included in the model, while in practice this can be a main determinant of the attractiveness of a train connection. A greater consideration of frequency would require additional assumptions on the time-value of certain frequency thresholds or more complicated agent-based models, which is why we abstain from it for this study, but we see it as having important potential to improve the model further. Data limitations in our case also prevent a more accurate modelling of change-over times, which would be desirable. Third, we use the same functional urban areas based on 2015 data for all analysis years, even though functional spatial relations were not the same in 1990, particularly along the former inner-German border. In addition, changing rail accessibility itself might have altered the delineation of some of the functional areas. This represents a methodological blur that we accept in order to avoid other, potentially more grave distortions induced by changing spatial units. Last, the dataset is timetable-based, i.e. does not consider delays, which we assume to occur evenly across the network.

2.4.4. Datasets

The spatial base units of our analyses are 266 functional city-regions ("Stadt-Land-Regionen") developed by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development.[6] They are homogenous, continuous, non-overlapping areas free of exclaves, based on the functional interlocking between urban cores and their hinterlands. This avoids difficulties arising from the heterogeneous definition of administrative areas even of the same hierarchical level between the German federal states. In the four-hour buffer zone, we use an additional 209 NUTS-3 areas[7] as an approximation of functional urban areas, which are of a similar spatial extent.

We use four rail network datasets of Germany for the years 1990, 2000, 2010 and 2020. The year 1990 was chosen as base year since it represents the situation before the opening of the first high-speed rail line in Germany (1991). Ten-year intervals provide a balance between data economy and detail of results. For each functional city region in Germany and each NUTS-3 region in the four-hour buffer zone, a main station was defined based on the highest number of departures per day, or, where this was ambiguous, based on centrality and importance in

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[6] https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/Raumabgrenzungen/deutschland/regionen/StadtLandRegionen/StadtLandRegionen.html?nn=2544954 (16.12.2020).

[7] https://ec.europa.eu/eurostat/web/nuts/nuts-maps (16.12.2020) (2016 classification).

the local context. All regions were served by rail in all analysis years, however in some cases the main station changed over time (e.g. Potsdam, Jena).

The dataset contains the fastest travel times of all regular train connections between the main stations, based on historical and current timetable data. The data was obtained from multiple sources, historical printed versions as well as current official online timetables and digitalised historical timetables.[8] Accuracy of the sources was tested by comparing a set of randomly selected records with the printed timetable.

A connection is considered 'regular' if it runs at least once every two hours over a period of eight consecutive hours on a working day. In very few cases connections with a lower frequency than 120 minutes were included, if otherwise a region would be unconnected. If the fastest connection between two main stations required an interchange at a station not included in the dataset, this station was added to the dataset but received no weight. This resulted in a network of 622 nodes and 984 edges in 1990, growing to 817 nodes and 1350 edges in 2020. For interchanges at stations, a changing time of two minutes was assumed, since the introduction of integrated fixed-interval timetables mean that connections are often seamless and timed. The resulting data can be accessed in a digital repository (Wenner and Thierstein 2020a).

2.5. Results

This section describes our findings. It is structured as follows. First, we show the distribution of accessibility by region separately for the different points in time 1990, 2000, 2010 and 2020, respectively. Next, we visualise the changes of accessibility during this period. Finally, we present results on the question of whether the changes amount to an increase or decrease in regional accessibility disparities.

2.5.1. Regional Accessibility Distribution

Figures 2-1 to 2-4 show the accessibility of population in terms of business trips by rail (potential accessibility, choropleth colours) and the number of other regions that can be reached without changing train (degree centrality, point symbols) for regions in Germany for the years 1990, 2000, 2010 and 2020. The accessibility values are normalised on the highest value in 2020, Köln as 100. Relatively high accessibility values close to a border are due to the inclusion of the four-hour buffer zone in the calculation that was omitted for the visualisation.

[8] https://www.fernbahn.de/datenbank/suche/#form2 (16.12.2020). Fully digitalised and searchable historical timetables, like the one supplied by Markus Grahnert, are often provided on the private initiative of railway enthusiasts and constitute a novel and promising source for spatial research into the development of accessibility.

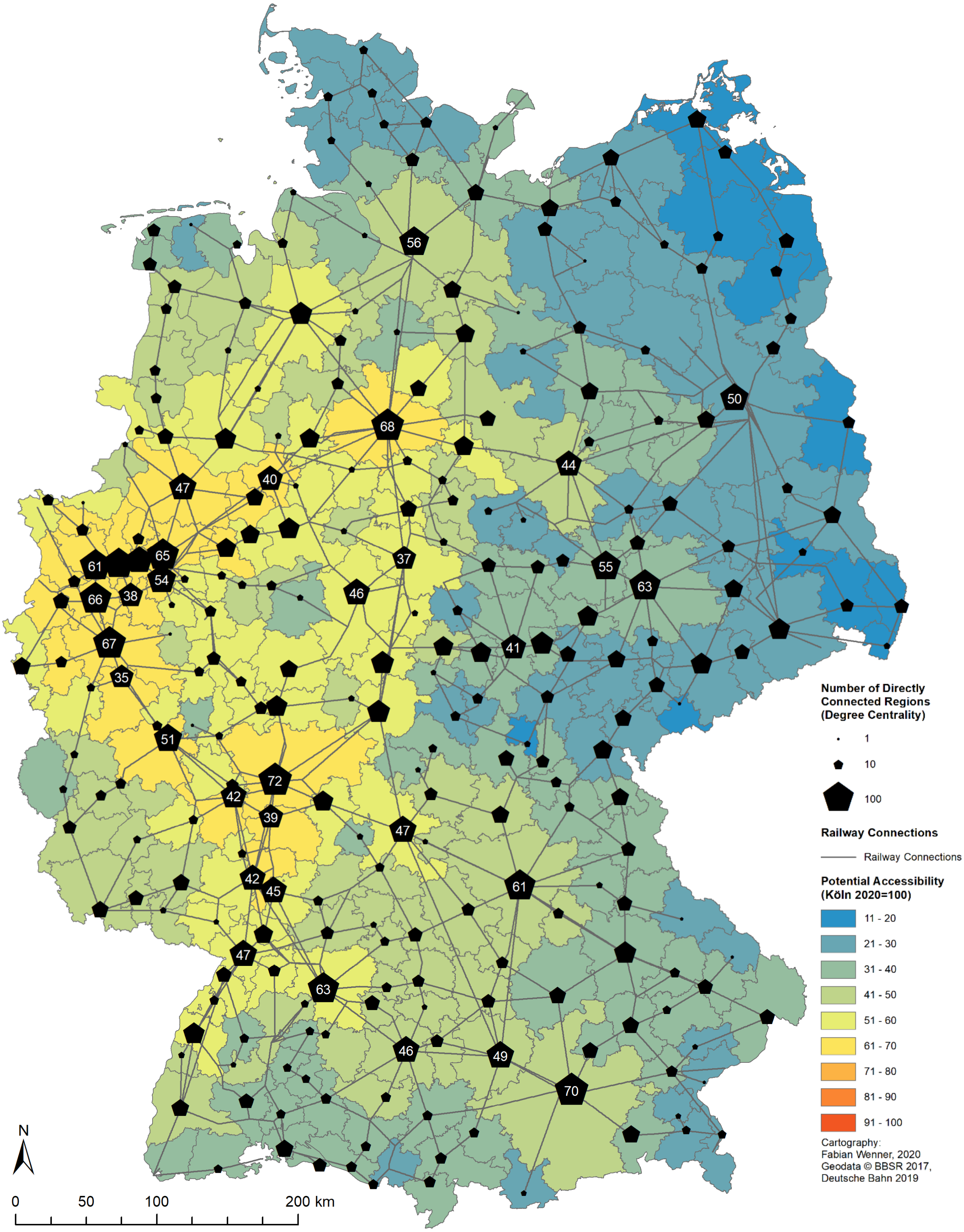

***Figure 2-1**: Regional Rail Accessibility and Degree Centrality in Germany in 1990*

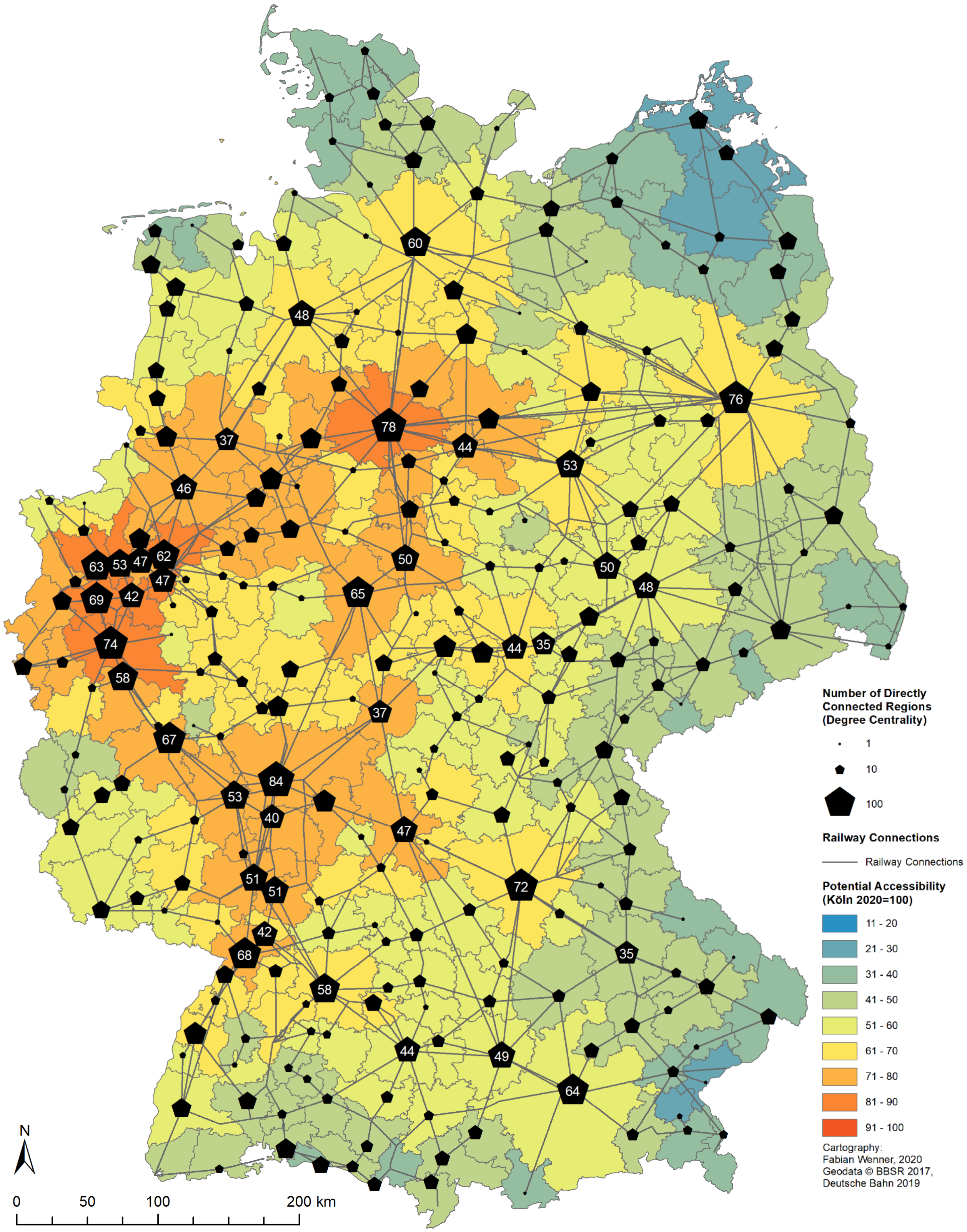

***Figure 2-2**: Regional Rail Accessibility and Degree Centrality in Germany in 2000*

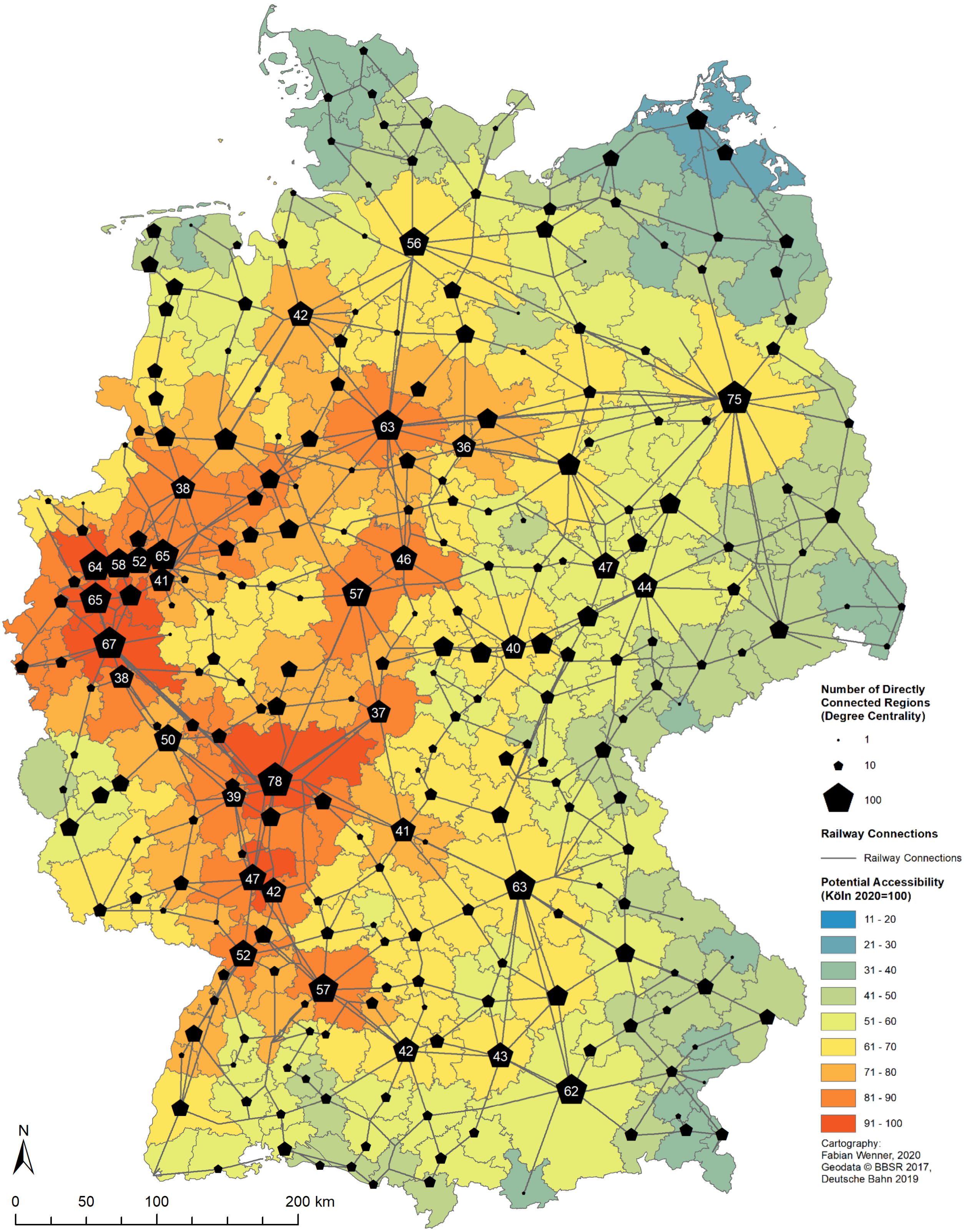

Figure 2-3: Regional Rail Accessibility and Degree Centrality in Germany in 2010

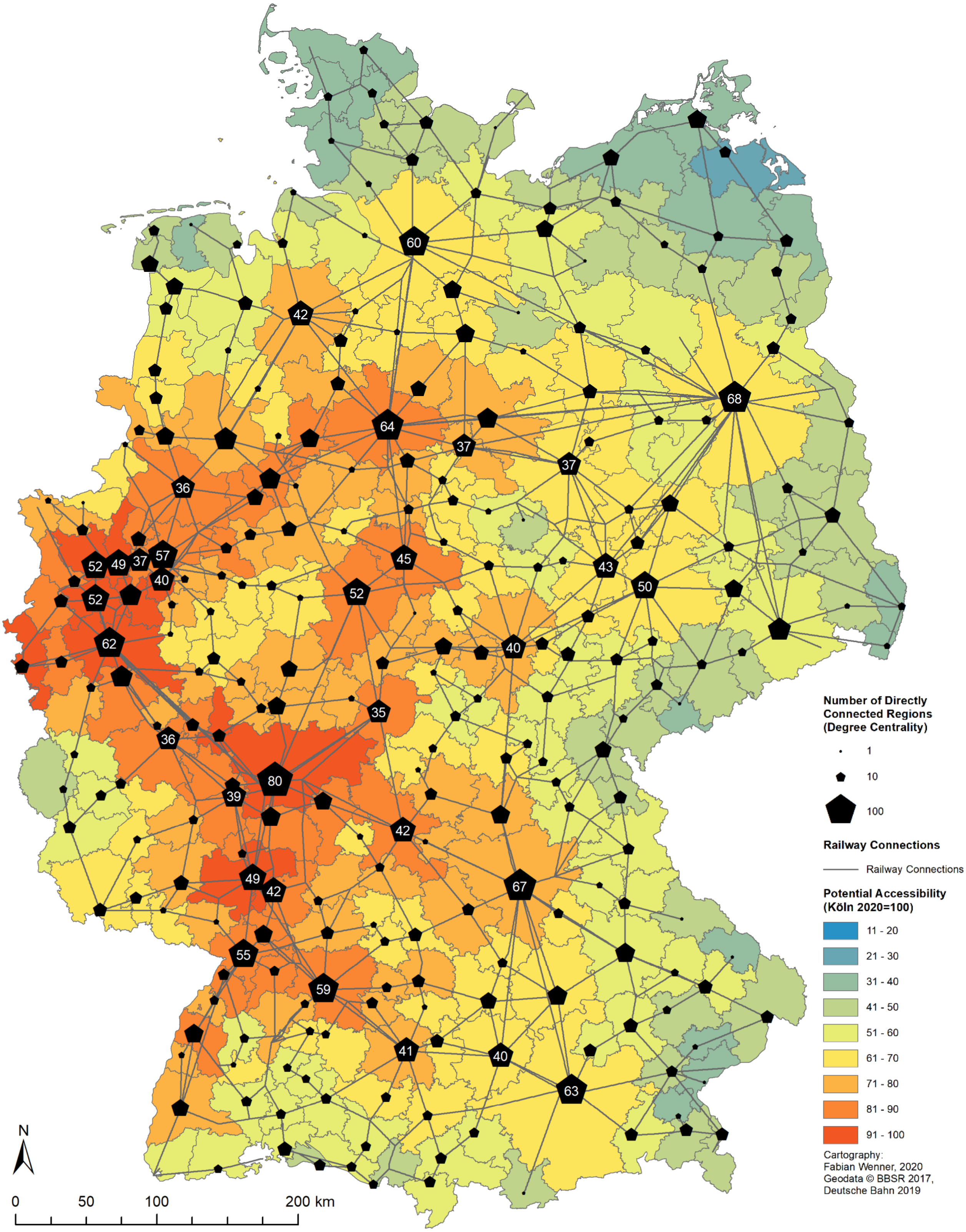

Figure 2-4: *Regional Rail Accessibility and Degree Centrality in Germany in 2020 (Source: Wenner and Thierstein 2020b: 66)*

The figures show a clear general trend of overall rising potential accessibility while at the same time the general spatial distribution of accessibility is largely preserved. The most accessible regions by rail are those of the western arc along the Rhein and the Rhein-Ruhr area throughout the study period. The accessibility distributions loosely resemble a smoothed-out population density map, suggesting a relatively evenly developed railway network, albeit with some deviations along the main rail corridors between the Rhein-Ruhr area and Berlin, and along the north-south corridor between Hannover and Frankfurt. The clear distinction of the former inner-German border vanishes after the first decade. The capital Berlin, as well as the second and third largest cities in Germany, Hamburg and München – all rather monocentric in spatial structure – exhibit only upper-medium accessibility values. Köln is rather the region with the highest rail accessibility throughout the study period, while Frankfurt main station constantly shows the highest degree centrality. Both cities are located in polycentric regions, but are also more centrally located with respect to the other metropolitan areas in the country. The results hence confirm the previous study by BAK Basel Economics (2007: 19). Nevertheless, the figures also show the existence of inner and outer peripheries with respect to rail accessibility. Whereas the western-most regions are part of a continuous urbanised zone in the core of Europe that is well-linked by rail, regions along the northern and eastern borders show low accessibility values despite the inclusion of a buffer zone, indicating poor rail integration and low population potential.

Table 2-1 shows the ten most and least accessible regions by rail in Germany in 1990 and 2020 by potential accessibility of population. The shift of the gravitational centre towards the south becomes clear: Frankfurt, Mannheim and Ludwigshafen are now in the top ten, while the post-industrial cities of Duisburg, Essen and Wuppertal have moved downward. Cities that have reoriented towards services like Köln and Düsseldorf remain high on the list. These changes are clearly induced by the new high-speed rail lines between Köln and Frankfurt and between Aachen and Brussels, also signified by the appearance of Limburg and Aachen on the list. The alignment and location of new high-speed rail lines in recent decades, together with a population shift, has strengthened the south of Germany in relation to rail access. The lower end of the list has changed from an all-eastern composition to a mixed one in 2020. The regions are peripheral not only with regard to the rail system, but also geographically.

	1990		2020			1990		2020	
Nr.	**Region**	**Acc. Index**	**Region**	**Acc. Index**	**Nr**	**Region**	**Acc. Index**	**Region**	**Acc. Index**
1	Köln	69.28	Köln	100	257	Senftenberg	19.80	Aurich	37.25
2	Duisburg	69.22	Frankfurt a.M.	97.29	258	Aue	18.94	Aue	36.98
3	Düsseldorf	68.90	Düsseldorf	96.15	259	Prenzlau	18.78	Eggenfelden	36.92
4	Essen	68.00	Mannheim	95.14	260	Stralsund	17.88	Torgelow-Ferdinandshof	36.68
5	Wuppertal	67.74	Duisburg	94.52	261	Torgelow-Ferdinandshof	17.41	Burghausen	36.10
6	Dortmund	67.19	Wuppertal	93.92	262	Bautzen	17.37	Husum	33.36
7	Hagen	66.84	Ludwigshafen	92.04	263	Greifswald	16.95	Zittau	32.81
8	Krefeld	66.71	Aachen	91.74	264	Görlitz	14.67	Flensburg	31.90
9	Bochum	66.41	Essen	91.59	265	Sonneberg	13.52	Stralsund	30.17
10	Bonn	66.21	Limburg	90.71	266	Zittau	11.04	Greifswald	28.78

***Table 2-1**: The ten most and least accessible regions by rail in Germany in 1990 and 2020 (Accessibility Index: Köln 2020 = 100)*

2.5.2. Dynamics of Accessibility

Figure 2-5 shows the cumulative relative accessibility changes for the 1990-2020 period as well as the new high-speed rail lines opened during this time with their opening years. Italic labels are placed in the regions with the highest and lowest potential accessibility gains in this period, ranging from +285% (Sonneberg) to +19% (Kleve). Rail accessibility changes in Germany in recent decades seem to have transcended the classical core-periphery dichotomy, showing rather a macro-regional pattern.

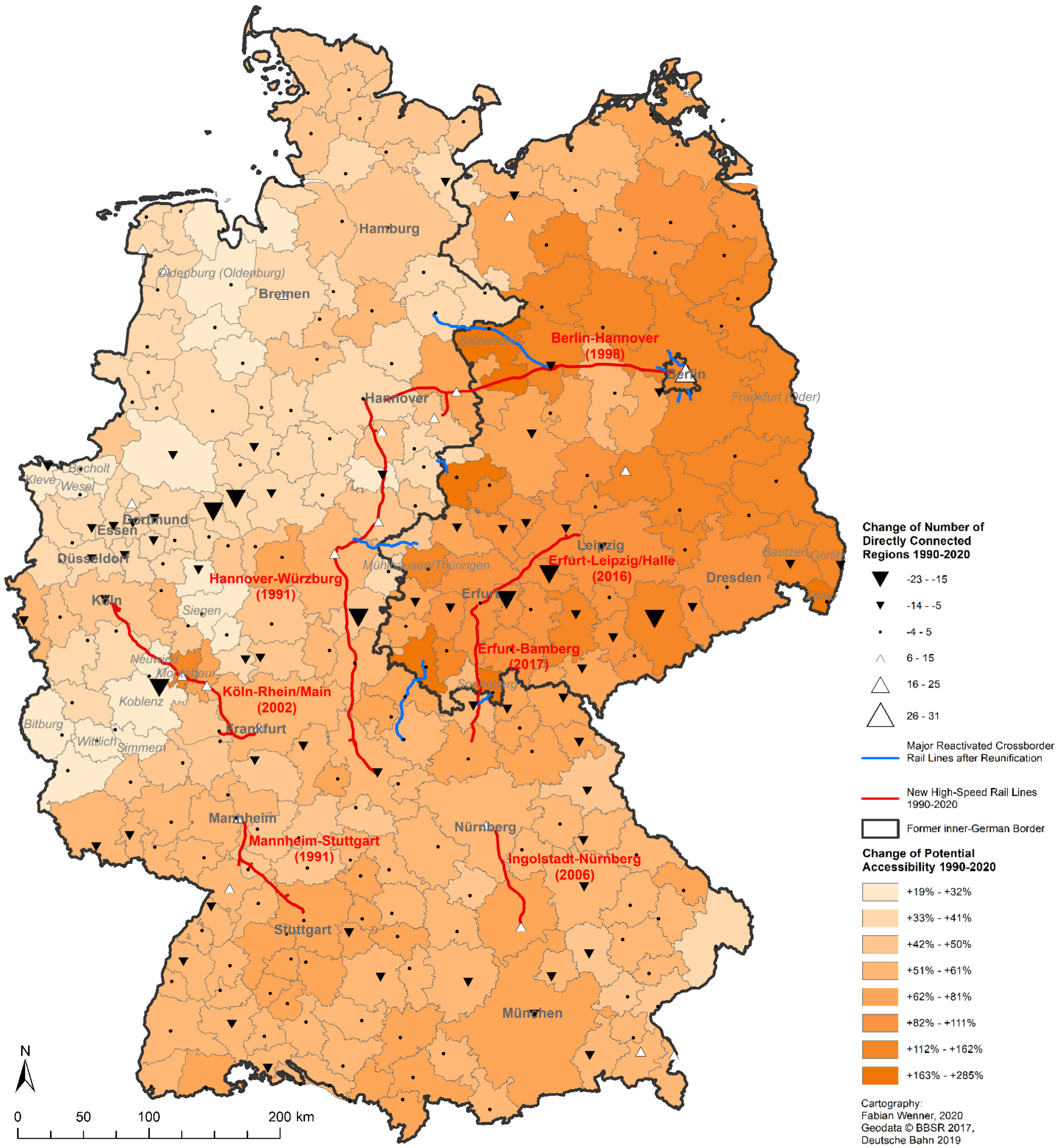

Figure 2-5: Change of Regional Rail Accessibility and Degree Centrality in Germany 1990-2020

In total, four influences on rail accessibility changes can be identified (for some regions, more than one characteristic applies):

- A general area-wide positive effect on accessibility of the renovation of rundown conventional rail infrastructure in eastern Germany after reunification in 1990 (strongest in the first decade). This effect largely overshadows the other effects.
- Particularly strong relative increases of accessibility in formerly peripheral regions along the inner-German border, especially in eastern Germany (e.g. Sonneberg, Meiningen, Salzwedel and Wernigerode) due to the re-establishment of dismantled cross-border lines.

- Significant gains of both relative accessibility and direct connections in regions on domestic and international high-speed rail lines (e.g. Aachen, Ingolstadt, Kassel, Wolfsburg) are particularly strong in less populous regions coincidentally located along new lines (e.g. Limburg, Montabaur). Positive accessibility effects expand farther in a funnel-shaped pattern beyond the ends of new high-speed rail lines while flanking regions usually do not profit. By-passed regions lose direct connections but not accessibility, as more people can now be reached in the same time, albeit with a necessary changeover (e.g. Bad Hersfeld/Bebra, Jena, Koblenz, Magdeburg and Naumburg). This is linked to the advantages of the integrated implementation of high-speed rail in Germany with mixed conventional/high-speed rail traffic and frequent interchanges.
- Reductions in the number of directly connected regions, as a result of the rationalisation and reorientation of rail services on the most profitable inter-metropolitan routes in the wake of DB's privatisation. This meant a reduction of slower but direct long-distance connections along less populated corridors such as the central east-west connection Halle-Kassel-Rhein/Ruhr area and the corridor along the eastern border Dresden-Hof-Regensburg-München, along with the re-emergence of the capital Berlin as the leading eastern hub. The number of people living in regions directly served by long-distance rail has consequently decreased (1990: 61.3m, 2020: 56.6m).

Regions that were affected by neither of these influences show a stagnation of accessibility, particularly those in some west-German 'inner peripheries' with respect to the rail network (e.g. Bitburg, Oldenburg and Siegen). No region experienced a decline in accessibility, even though several regional cross-border lines with the Netherlands were closed during the study period despite accelerating EU integration.

2.5.3. Increasing or Decreasing Accessibility Disparities?

To show more clearly the winning and losing regions in relative terms, we consolidate the rail accessibility changes into a four-category matrix according to their previous standing and their accessibility change (Figure 2-6, cf. Stępniak and Rosik 2016: 9). Above average increases with a low baseline accessibility, which are instrumental for territorial cohesion, can be found in large parts of the eastern regions, particularly Erfurt, Leipzig, Dresden and Berlin, with their wider surroundings. Here, the effects of general infrastructure upgrade and high-speed rail complement each other, confirming Holzhauser and Steinbach (2000). Likewise, the below average increases in large parts of north-western Germany have a positive influence on cohesion, but show that constant accessibility levels can result in a relative loss of attractiveness. However, the figure also reveals a pattern of consolidation of high accessibility mostly in the south-western regions that are already well endowed in terms of rail accessibility. This reflects the alignment and spatial pattern of high-speed rail investment in recent decades. Anti-cohesion effects can be furthermore observed in large parts of the geographically peripheral areas in the north, southeast and south.

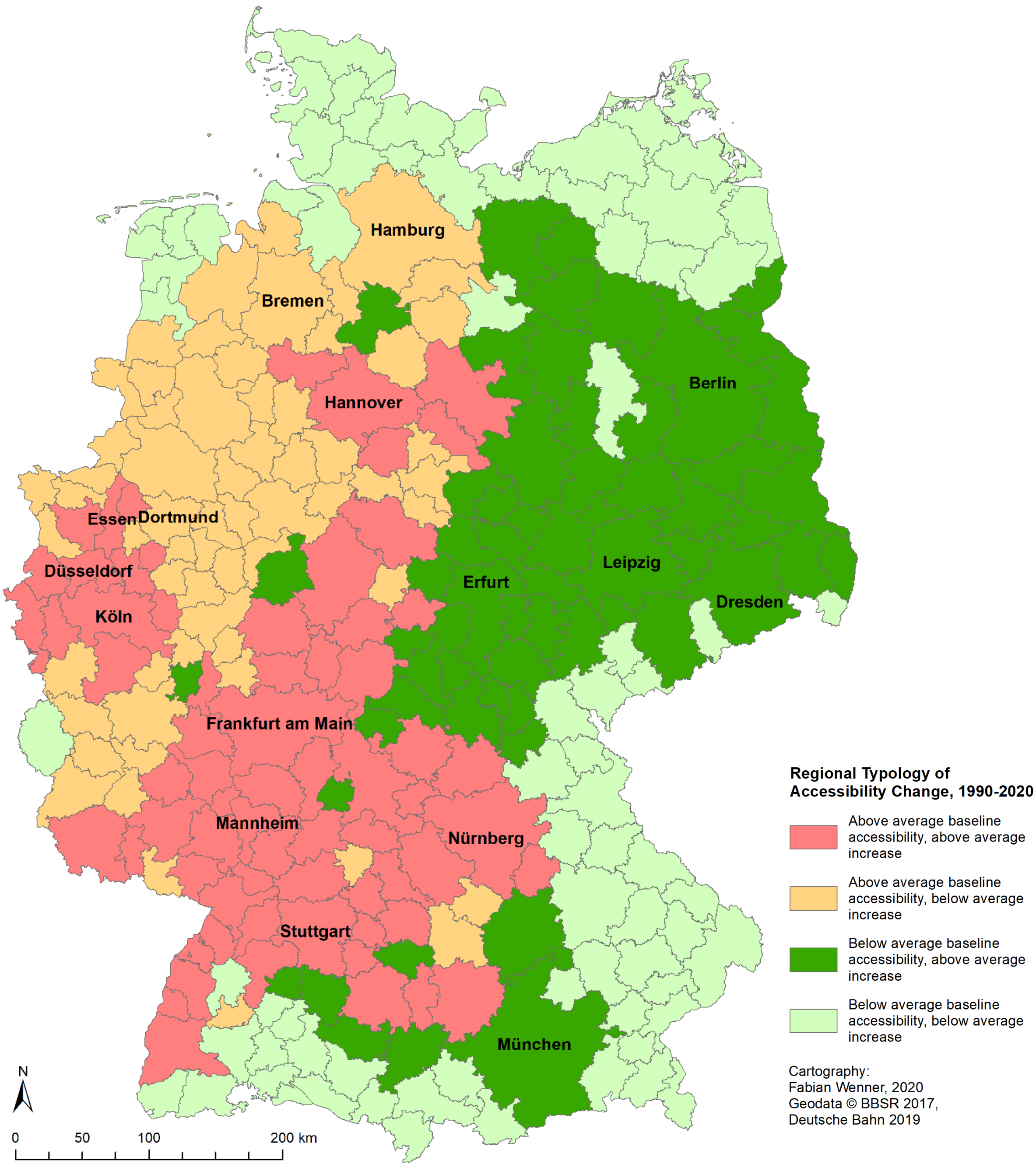

Figure 2-6*: Typology of Regions by Accessibility Structure and Dynamics, 1990-2020*

Next, we compare an alternative scenario with the rail network of 1990 but the population distribution of 2020 with the actual results, in order to differentiate between effects of rail infrastructure and population development (Figure 2-7). The share of population growth in accessibility increases varies between 2% and 43%, the share of network effects between 57% and 98%. After reunification in 1990, about 1.5 million people moved from the new to the old federal states. Nevertheless, it is surprising how clearly the former inner-German border can be identified. Accordingly, in eastern Germany, accessibility growth was almost completely due to network improvements. Had the network remained in its 1990 state, accessibility growth of peripheral eastern regions like Görlitz would have been minimal, mostly due to the far-reaching effects of population growth in Berlin and other urban areas that compensate local population losses. On the other hand, in some of the regions with the lowest overall accessibility growth, even this growth was mainly due to population increases. Rail investment has hence not followed population growth (as e.g. in Spain, Condeço-Melhorado, Zofío and Christidis 2017), but was deliberately concentrated on depopulating regions as structural aid, at least during the study period. This is also underlined by the fact that regions of the "disproportionately shrinking" and "shrinking" type in terms of population (following the classifications of the BBSR) have experienced significantly higher accessibility gains than other types in the 1990-2000 period, while in the later periods there is no clear difference between the types.

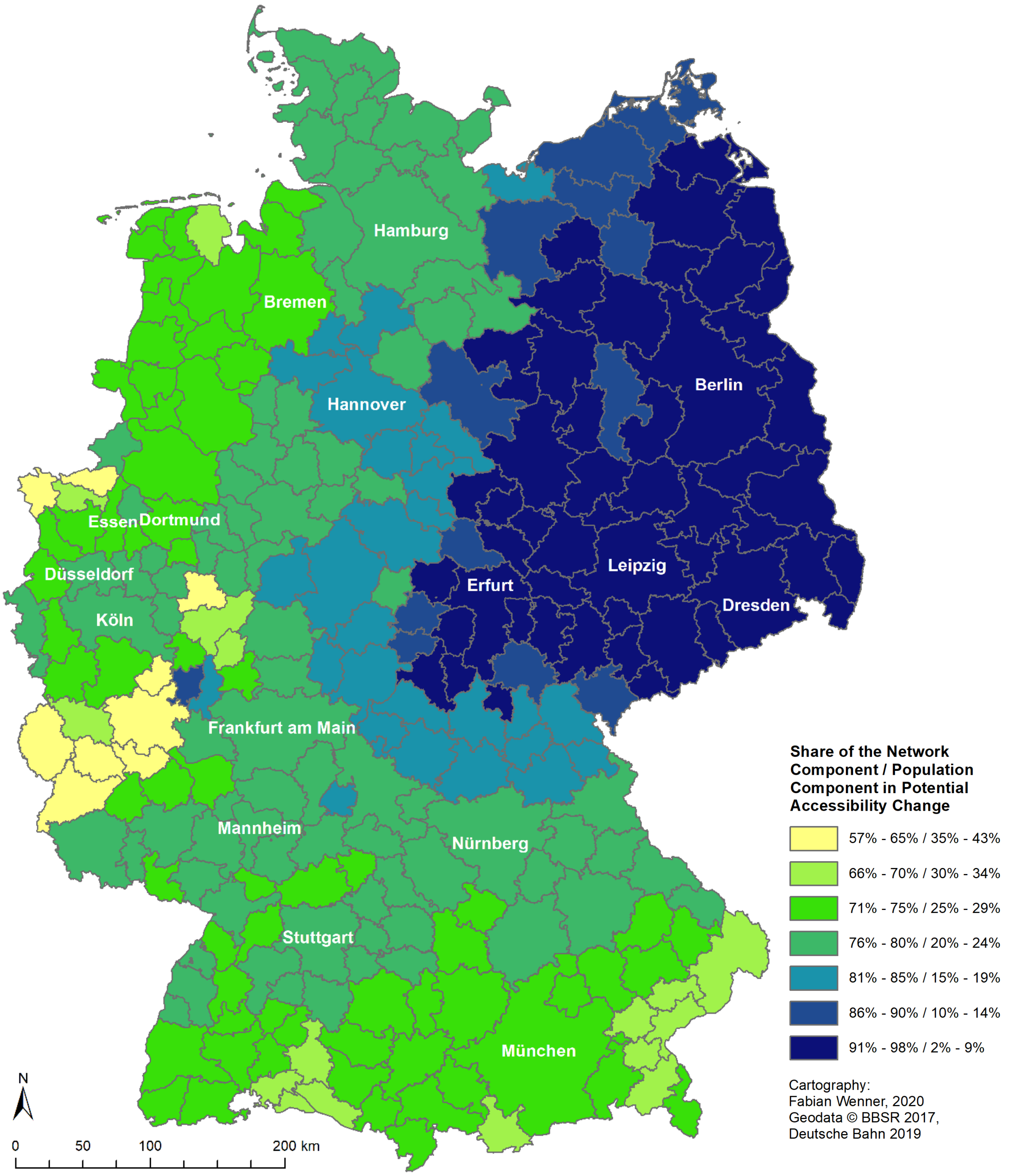

Figure 2-7: *Share of the Network and Population Components in Potential Accessibility Change*

Sorting all regions by accessibility rank (Figure 2-8), one can observe an upward shift of the accessibility levels rather than a change of the slope, similar to the results of Axhausen, Fröhlich and Tschopp (2006: 18) for Switzerland, despite less growth at the lower end in recent decades. However, this level shift means that the least accessible regions now have a higher share than the most accessible regions. The shift is markedly stronger for the 1990-2000 period. Persistent outliers can be found at both the upper and lower ends of the curve. While Spiekermann and Wegener (1996: 41) predicted an increasing Gini coefficient of rail accessibility and hence greater inequality on the European scale between 1993 and 2010, we find a decrease of the Gini coefficient of accessibility for German regions from 0.169 to 0.116 between 1990 and 2020. Likewise, the so-called Accessibility Dispersion (AD) index, sometimes used to evaluate the impacts of transport infrastructure development on territorial cohesion (Ortega, López and Monzón 2014: 18), decreases from 0.284 to 0.211 during the study period. Lower AD values indicate a more balanced distribution of accessibility. We find this cohesion effect to be mostly limited to the period of 1990-2000 however, with only minimal changes afterwards. The Gini coefficient of degree centrality increases from 0.390 to 0.412 in the same timespan, confirming the observation of a greater concentration of direct interregional connections in metropolitan hubs.

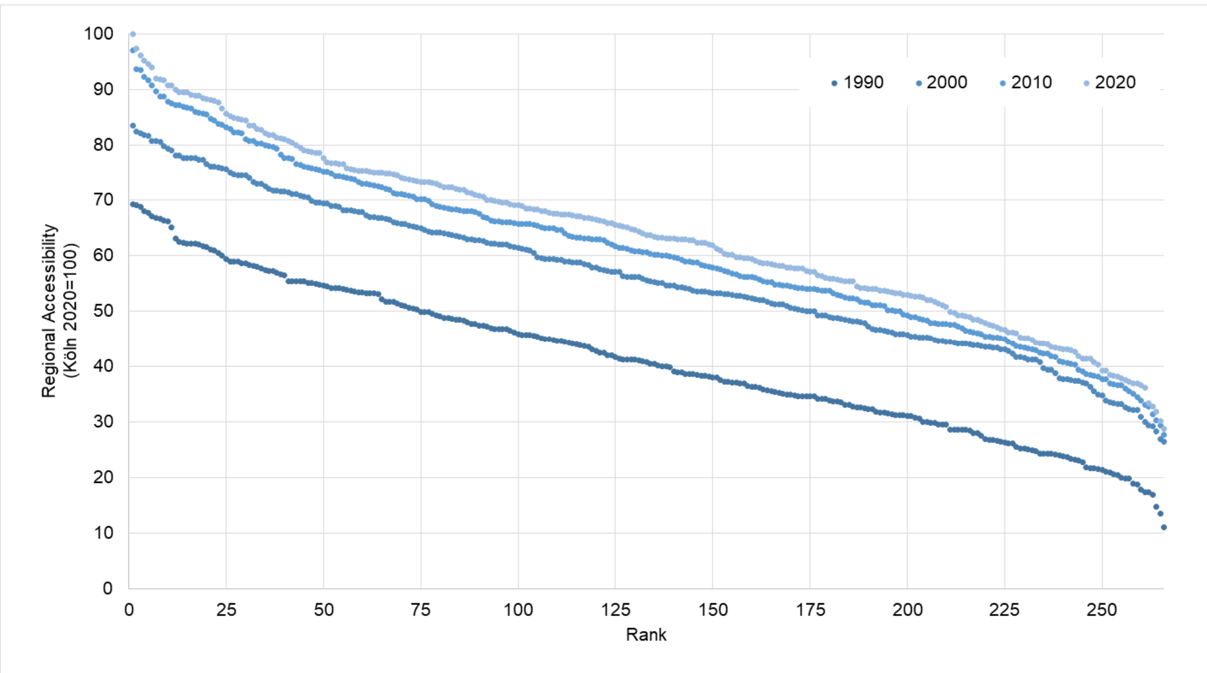

***Figure 2-8**: Distribution of regional rail accessibility in Germany by rank, 1990-2020*

2.6. **Conclusion and outlook**

This paper has reviewed previous studies of regional rail accessibility in Germany and complemented them by an analysis of changes in rail accessibility of 266 functional urban areas in Germany for four points in time: 1990, after German reunification and before the introduction of high-speed rail, 2000, 2010 and 2020. The study used a potential accessibility measure based on an exponential decay function calibrated for business trips, and a degree centrality measure for direct regional connections. The analysis confirms the general pattern of accessibility distribution with regions in the 'blue banana' of Europe exhibiting the highest accessibility levels. Regarding the dynamics, we find no evidence for growing rail accessibility disparities in Germany, despite the discontinuation of intermediate long-distance trains and the construction of high-speed rail infrastructure. Instead, there has been an accessibility increase across all regions throughout the study period. High-speed rail has led to extraordinary accessibility improvements in some cases, but the refurbishment of conventional rail lines and reopening of formerly dismantled cross-border lines in eastern Germany after 1990 have largely overshadowed the effects of high-speed rail, particularly in the first decade after reunification. Regarding degree centrality, we find a reduction of direct change-free connections between regions in favour of a concentration of long-distance lines on major metropolitan hubs.

High-speed rail effects in Germany have furthermore transcended the classical urban-periphery dichotomy and are spatially more extensive, but also more discretionary than in other European countries. This is due to the interlinkage of high-speed and conventional rail, the more dispersed settlement structure and piecemeal implementation of high-speed rail. Unlike in other countries, the most accessible region is not the capital city. We find a cohesive development of rail accessibility during the study period, which can however mostly be attributed to the first decade, 1990-2000, and has since come to a halt. Since then, both population development and the alignment of new high-speed rail lines have strengthened the accessibility of southern German regions.

The chosen approach has limitations. Particularly, the results might contrast with the local experience of rail line closures and discontinuation of services in the 1990s and 2000s. However, the study takes regions as spatial base units, which means that local lines within regions are not considered. Further improvements of the analysis should contrast the findings with accessibility for other modes, particularly road and air, also multi- and intermodally, and take generalised costs into account rather than pure time costs. Furthermore, recent studies have used a more time-geographical perspective and have highlighted the critical importance of certain time thresholds with regard to high-speed rail business trips (e.g. Chen and Hall 2011; Moyano, Rivas and Coronado 2019). This perspective could be fruitful for further research regarding the German public transport system, as it is not yet considered widely in interregional transport. The analysis of betweenness centrality would likewise reveal changes in the importance of certain regions as hubs.

This paper has concentrated on travel times between regions as the main determinant of accessibility. For an integrated and seamless transport system, which is the policy goal of the current Federal Transport Infrastructure Plan and its "Deutschland-Takt", well-timed interchanges are more important than speed alone. Instead, 'sufficient' travel times between interchange nodes should guide infrastructure investment. A refinement of the methodology used here could take interchanges into account more explicitly.

Finally, it is interesting to reconsider that two of the first high-speed rail lines (Hannover-Würzburg, 1991; Berlin-Wolfsburg, 1998) were planned and partially constructed before German reunification, in a way that bypassed or transited East Germany. Transport infrastructure is costly, changes slowly and potentially has long-lasting implications on flows of people, goods and services. The accessibility maps shown in this paper would likely look different had reunification occurred earlier, pointing to the potential role of 'longue durée' (Braudel 1958; Wallerstein 1979) processes in regional economics.

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3. Which Regions Benefit from New Rail Accessibility? Germany in 2030

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Abstract: New transport infrastructure alters the spatial distribution of accessibility, which can influence a region's development potential. The implementation of High-Speed Rail (HSR) during the last decades has often considerably improved rail accessibility of connected regions, but is also often found to increase relative discrepancies between regions. We analyse the effects of currently planned rail projects on regional accessibility in Germany, with a spatial and network structure differing from other countries, for the year 2030. We use a population potential and a degree centrality measure and find slight tendency towards greater balancing of accessibility across regions and greater poly-centralisation within the rail network, showing the importance of network integration and improvements beyond the HSR network. Two macro-regions of Germany profit most from the planned rail lines: the economically dynamic South and the catching-up East. We interpret this as the outcome of two simultaneous planning goals which include removing "bottlenecks" and supporting weaker regions. We propose that the official regional planning assessment currently used in the planning process of national rail infrastructure could be improved by applying a potential accessibility measure.

Contributions (CRediT taxonomy): Conceptualisation, F.W.; methodology, F.W.; validation, F.W., A.T.; formal analysis, F.W.; investigation, F.W.; data curation, F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W., A.T.; visualisation, F.W.; supervision, F.W., A.T.; project administration, F.W.

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3.1. Introduction

Rail as a transport mode has experienced a remarkable resurgence in the last decades (Banister and Hall 1993), particularly in Europe, characterised by increased ridership and investments. A range of factors can be identified for contributing to this resurgence, among them ecological advantages, but also technological advancements and service improvements. The introduction of High-Speed Rail (HSR) with speeds of up to 320 km/h has reinforced the competitive position of passenger rail over air and road transport, but it can also influence the spatially differentiated distribution of rail accessibility.

While the effects of accessibility on regional economic development are subject to debate, there is a more general need for studies that analyse, quantify and visualise accessibility changes per se and in comparative perspective across regions and longer timespans (Stępniak and Rosik 2018: 309; Axhausen 2012: 12; BBSR 2019: 103). This relates particularly to the effects of HSR on regional accessibility. On the one hand, it is argued that HSR disproportionately benefits central regions, particularly where parallel conventional rail services are reduced or discontinued (Spiekermann and Wegener 1996: 38). Other studies, however, find a positive effect of HSR on accessibility equity, at least if it is well integrated with the conventional rail network.

While the fast-growing rail networks of China and Spain have attracted high research interest recently, there are few studies on rail accessibility changes with respect to Germany despite almost 30 years of HSR implementation. The federal political decision-making and dispersed settlement structure in Germany means that HSR implementation differs from more centralised settings with respect to station placement, integration with conventional rail systems and local transport, as well as network structure and alignment, which makes it an interesting case study. The most recent transport infrastructure plan for Germany envisages further substantial investments in the rail network until 2030, following a two-fold approach. On the one hand, eight HSR lines or upgrades are planned, while simultaneously there is an ongoing examination for improving the conventional rail network through improved interchanges and more direct interregional connections. This paper focuses on the spatial distribution patterns of accessibility changes caused by this integrated approach.

In this paper, we quantify and visualise the rail accessibility changes introduced by the currently planned rail projects in Germany until 2030 on a regional level. The paper is structured as follows: section two presents a short literature review on rail accessibility changes in the European context and their relation to regional economic development; section three introduces the situation of rail transport in Germany and the currently planned infrastructure projects; section four introduces the methods and datasets used to analyse rail accessibility differences between 2020 and 2030; and section five describes our results. We then conclude in section six with a discussion on our findings and present an outlook on further research.

3.2. High-speed rail and rail accessibility changes

Heightened political interest and investment volumes have contributed to an increased research concern with the spatial features and development effects of rail infrastructure improvements during the last decades. Nevertheless, the influence of accessibility on regional development is disputed. On the one hand, neoclassical economic theory assumes long-term convergence between regions. In this view, persistent inequalities can be the result of barriers to the free movement of production factors (Barro and Sala-i-Martin 1992; Solow 1956). Under the neoclassical framework, reduction of travel times leads to an improved allocation of resources and an increase in overall productivity through knock-on effects in the private sector (Aschauer 1989). Accounting for economies of scale, they also potentially enable positive spillovers from agglomeration and network effects, particularly in the case of small and/or peripheral regions (Andersson and Karlsson 2004; Reggiani et al. 2011; Ahlfeldt and Feddersen 2018). Within regions, location theory can explain the sorting of activities in space under equilibrium conditions according to accessibility (Alonso 1964; Weber 1909). Rail accessibility can hence be considered as a locational factor for firms and households (Axhausen 2008: 5; BMVI 2016: II). While rail access has so far been an important factor especially in freight transport, this is increasingly also the case in the tertiary sector, particularly in the European context. It represents an important means for establishing and maintaining ties to business partners, aided by the fact that rail travel time can be used for work purposes and that it often provides direct city-centre access. The shift towards a knowledge-based economy (Lüthi, Thierstein and Bentlage 2013) supports this trend.

On the other hand, theories that emphasize cumulative causation and path dependencies, such as the "new economic geography" (NEG) (Krugman 1998) predict persistent regional differences and further agglomeration of firms and workers in successful regions despite – or precisely because of – an improvement in interregional transport infrastructure. Accessibility increases can be detrimental for peripheral regions previously 'shielded' from competition from the core (Puga 2008). Under these conditions, regional development should be focused on strengthening endogenous regional potential rather than improving transport connections.

Hence, the relationship between rail accessibility and regional economic development seems to be neither universal nor automatic (Chen and Hall 2011). Moreover, effects may be redistributive rather than generative, which also means that accessibility relative to other regions, not in absolute terms, might be decisive for economic outcomes (Vickerman 1987: 189).

However, not only the link between accessibility and economic development remains disputed. With respect to European case studies, scholars have also questioned the location and strength of accessibility changes themselves, which were induced by recent rail infrastructure investments, particularly with the introduction of HSR. Several studies associate HSR with an increase of accessibility disparities between regions and hence economic discrepancies or at least new layers of advantages and disadvantages on a European (Spiekermann and Wegener 1996: 38) and national scale (Stiens 1992; Plassard 1994: 61). High construction and running costs mean that HSR is usually first implemented between the most populous and economically dynamic regions, improving their connection and mutual accessibility, but not that of the area in between (often called "tunnel effect"). In some cases, their accessibility is reduced in absolute terms, when parallel conventional rail connections with more frequent stops are discontinued entirely. Moreover, even if absolute accessibility of the remote region increases, these gains are often overshadowed by those of the core. Hall (2009: 65) calls this the "peripheralisation of the periphery."

At the same time, a number of studies have found beneficial effects of HSR for reducing regional accessibility disparities on a European (Gutiérrez, González and Gómez 1996) and national level (Gutierrez 2001; Monzón, Ortega and López 2013; Monzon, Lopez and Ortega 2019), also in terms of the symbolic dimension for cohesion. Many authors point out the importance of mixed high-speed and conventional services and intermodal interchanges as important elements to spread accessibility benefits to a wider area (Vickerman 1997: 32; Givoni 2006; Chen and Hall 2013; Marti-Henneberg 2015).

Regarding the general distribution of rail accessibility in Europe, most studies confirm the well-established "blue banana" (Brunet 1989) pattern of an arch of high population density in North-Western Europe with the highest accessibility of population (e.g. European Commission 2016), while Martín and Reggiani (2007: 558) describe a shift of the centre of gravity within the EU from Paris eastwards in the decade between 2007 and 2020. Rail accessibility is also typically less homogenous than road accessibility: Some (mostly rural) regions that are geographically central within Europe are much less accessible than the agglomerations (Spiekermann and Neubauer 2002: 26), while on the other hand, agglomerations, typically the capitals of countries that are geographically peripheral within Europe, can nevertheless exhibit a high level of rail accessibility (Lutter, Pütz and Spangenberg 1993).

While there is rich literature on regional accessibility (including rail) on a European scale, starting with Keeble, Owens and Thompson (1982) (see ESPON (2015: 46-55) for a comprehensive overview), and a large number of studies on the fast-growing HSR network in Spain (e.g. Ribalaygua and Perez-Del-Caño 2019; Monzon, Lopez and Ortega 2019), only a few studies have analysed the development of the rail system in Germany, despite the fact that the first HSR line has been in operation for almost 30 years. Those that exist are often dated. Schliebe and Würdemann (1990) estimated an average rail travel time reduction between German regions of 45 minutes between 1990 and 2000. Using a contour-based travel time model without distance decay, they estimate that a high number of region pairs will fall within the critical four-hour threshold for daily return business trips. Beneficiaries are particularly the (then capital) city of Bonn, and the West in general, while their prognosis for Berlin is less advantageous. According to prognoses of Steinbach and Zumkeller (1992), HSR would lead to the creation of a continuous zone of equally high rail accessibility throughout south-west Germany. Holzhauser and Steinbach (2000) simulate the accessibility effects of rail projects after German reunification and conclude that the economic cores of Eastern Germany (particularly Saxony, Saxony-Anhalt and Thuringia) will profit most, thereby balancing accessibility across the country's regions. In addition, Berlin will be released from its peripheral position.

More recently, Evangelinos, Hesse and Püschel (2011) calculated a combined rail accessibility indicator for Germany consisting of gravitational accessibility of economic output, daily accessibility of population within four hours, and relative network efficiency. They found that Frankfurt by far dominates the ranking, followed by Düsseldorf, Hannover, and Köln with Trier being last. Wenner and Moser (2020) have found a strong decrease in accessibility disparities between 1990 and 2000, and a stagnation since then, which can mostly be traced back to conventional infrastructure improvements in Eastern Germany after reunification. The question remains open whether currently planned rail infrastructure improvements will favour certain types of regions over others in terms of accessibility changes, and whether it will benefit all regions, including peripheral ones.

3.3. Current and future HSR implementation in Germany

The vast majority of the railway infrastructure in Germany, as well as the operation of long-distance train traffic, is in the hands of the main railway company Deutsche Bahn (DB) AG, which however is obliged to grant equal access to competitors. The federal states, which have considerable bargaining powers in the German political system, have often – sometimes successfully – attempted to influence route alignment and station placement in favour of less populated or peripheral areas, which theoretically improves an equitable distribution of accessibility. The polycentric and dispersed settlement structure of Germany has furthermore meant that new HSR lines were not constructed radially from the capital, but in a rather fragmentary way between pairs of urban centres, redoubling busy sections of the conventional network. At the same time, this means that the HS network in Germany is not separate, as in several other countries, but is also used by conventional trains and the conventional network by HS trains. Most HS lines are furthermore equipped for freight train use at night, increasing construction costs.

The Federal Transport Infrastructure Plan (Bundesverkehrswegeplan, BVWP) is the most important tool for planning new transport infrastructure of nationwide importance. Developed by the Ministry of Transport, it forms the framework document for individual transport projects. The most recent BVWP was developed in 2016 with a time horizon of 2030. State governments, municipalities and associations, railway companies, but also private individuals can propose measures to be included in the plan. In the area of rail transport, around 60 project proposals were considered suitable for investigation (BMVI 2016: 39-41).

The proposals undergo a cost-benefit-analysis as well as environmental and nature conservation, regional and urban planning assessments. Proposals with a cost-benefit ratio below one are excluded from further process. The remaining proposals are prioritised in two categories based on the results of the investigation: urgent and further demand. Projects of "further demand" are generally desirable, but exceed the financial framework that is expected to be available until 2030. Only projects of "urgent demand" therefore have a chance of realisation in the timeframe of the plan. Based on the BVWP, detailed plans for each individual mode of transport are derived and passed as law by parliament.

However, the ultimate realisation of projects even of urgent demand depends heavily on the funds available. Funds are allocated to the three modes of transport (road, rail and waterway) according to political aspects. For expansion and new construction projects, the share of investments in road projects is highest at 53.6%, while railways account for 42.1% and waterways for 4.3% (BMVI 2016: 35). This means an investment of €46bn in rail infrastructure. A significant portion is allocated to unfinished "ongoing and firmly planned" projects from past BVWPs, whereas, some projects receive additional funding through the EU's TEN-T measures.

The BVWP's reasoning with regards to the selection of projects is largely demand-driven and aimed at eliminating "bottlenecks" and improving "traffic flow" (BMVI 2016: 6). Aspects of traffic safety as well as climate, environmental and noise protection are mentioned, but are explicitly not in the foreground. Territorial cohesion and equality of living conditions also play a subordinate role. The regional planning assessment analyses deficits in the quality of the connection between central locations of the highest two levels in the central place system, as well as accessibility deficits based on certain minimum standards. However, the chosen method of assessing only connections between directly neighbouring centres disregards many important connections. The accessibility analysis is spatially differentiated, but uses generous threshold values and does not differentiate between qualities of destinations.

A major innovation of the most recent BVWP in the rail sector is the inclusion of a separate project for a comprehensive, nationwide coordinated timetable, the "Deutschland-Takt" (BMVI 2019), similar to the Netherlands and Switzerland. The "Deutschland-Takt" is designed to optimise interchanges and thus ensure seamless travel chains. The infrastructure should then be adapted to the desired timetable, and not vice versa, as has often been the case before. A number of measures have found their way into the "urgent need" category because of this additional project, among them several high-speed rail lines such as the Bielefeld-Hannover and Nürnberg-Würzburg lines (see Table 3-1, refer to Figure 3-3 for a spatial representation). In addition, the project foresees the reintroduction of several long-distances lines through less populated corridors and tangential connections, as well as several completely new regular connections. Like the BVWP, it has a time horizon of 2030, but it is unlikely that all measures will be completed by then. Nevertheless, we use "2030" in this paper when referring to the final state of this timetable.

Line	**Type**	**Status**
Bielefeld-Hannover	New Line	Envisaged
Frankfurt-Mannheim	New Line	In Preparation
Fulda-Hanau	New Line	In Preparation
Nürnberg-Würzburg	New Line	Envisaged
Stuttgart-Ulm	New Line	Under Construction (2022)
Augsburg-Ulm	New Line	Envisaged
Eisenach-Fulda	New Line	In Preparation
Karlsruhe-Basel	New / Upgraded Line	Under Construction

***Table 3-1**: New High-Speed Rail lines included in the current BVWP after amendments of the "Deutschland-Takt" project (BMVI 2019)*

3.4. Methodology

The aim of the empirical part of this paper is to estimate changes in rail accessibility in Germany on a regional scale, induced by the scheduled infrastructure projects of the current Federal Transport Infrastructure Plan and its associated plan, the "Deutschland-Takt," until 2030. Specifically, we want to localise and quantify accessibility changes, and analyse whether the changes lead to a more equitable distribution of accessibility. In order to do this we develop a mono-modal accessibility model for two points in time: 2020 and 2030.

Accessibility is often defined based on Hansen (1959: 73) as the "potential for opportunities of interaction" of a locality and can be measured in various ways. An overview of different operationalisations of accessibility can be found in Song (1996) and Geurs and van Wee (2004). We focus on the "transport" and "land use" components of accessibility without differentiating by personal and time restrictions (Geurs and van Wee 2004: 129). For this study, we use two different accessibility measures, potential accessibility and degree centrality, which capture different dimensions of the accessibility concept. We consider gravitational accessibility to be a more realistic measure than closeness centrality, which does not include a distance decay, while daily accessibility depends more strongly on the chosen system boundaries. Betweenness centrality, on the other hand, is another highly interesting concept, but is more reliant on precise data on future timetables. We would like to refer readers who are interested in these indicators being applied to the dataset of this paper to Wenner and Moser (2020).

3.4.1. Potential accessibility

Potential accessibility measures are calculated by summing up all destinations that can be reached from a point in a network, weighted by their attractiveness (e.g. economic mass or population), and inversely weighted by their distance. They rest on the assumption that the likelihood for personal interactions, and consequently travel, from any location to another destination depends on the number of opportunities the destination presents, and the difficulty to reach it (Barthélemy 2011: 35). Such potential measures have been widely used in transport and urban geography. Here, we use an exponential distance decay function, also called gravitational function. Exponential functions match observations of travel behaviour well and are often considered superior to other functions (Song 1996: 479). They are also closely tied to travel behaviour theory (Geurs and van Wee 2004: 133; Handy and Niemeier 1997: 1177) and under certain circumstances their formulation can be shown to be a measure of the consumer surplus in a utility-based model (Williams 1977; Axhausen, Fröhlich and Tschopp 2006). The formula used has the form of eq. 3-1,

$$P[i] = \sum_{j \in G-\{i\}} \frac{W[j]}{e^{\beta * d[i,j]}} \qquad \text{(eq. 3-1)}$$

where P[i] is the potential accessibility of location i, W[j] the weight of destination j, d[i,j] is the travel time between locations i and j, and β is the exponent for adjusting the distance decay. We use population as destination weight since it represents a well available and neutral indicator of opportunities. Regional GDP or workplaces are alternative destination weights regularly used in literature. For the 2030 accessibility calculation, we do not make assumptions about population shifts and use 2020 population data to model more clearly the uninfluenced infrastructure effects. Even though travellers typically consider a wider set of characteristics for a journey, such as comfort and price, we concentrate here on travel time as the main attenuating factor for interactions. We assume other characteristics to be (partly) subsumed therein (Ingram 1971: 102), particularly since Deutsche Bahn applies a mostly distance-based fare system for flexible business travel tickets. Since the same restrictions apply to both time steps, the comparison remains valid.

The decay factor is scale-dependent and must hence be adjusted for each case study depending on the travel purpose and the demand characteristics, based on observed data or comparative cases from literature (Frost and Spence 1995: 1834; Geurs and van Wee 2004: 133; Geertman and Ritsema Van Eck 1995: 70). Greater distance decay exponents mean a stronger distance decay and are hence suitable for short-distance interactions with higher emphasis on the land use component whereas smaller exponents are used to model long-distance interactions. A good overview of decay factors for different scales and trip purposes can be found in Rosik, Stępniak and Komornicki (2015: 140). Östh, Reggiani and Galiazzo (2014) propose the distance decay to be calibrated using the median travel time typical for the travel purpose under consideration, but no recent statistical data for Germany is available. However, using distance-based values from Harrer and Scherr (2013: 65) one can deduce a decay factor of about 0.005, assuming an average speed of 90 km/h and omitting very shortrange trips. As the focus of our analysis is the (inter-)regional scale as well as medium-distance interactions e.g. for business trips and meetings, we chose a decay factor of 0.0057, which translates into a halving of interactions after 120 minutes of travel. This is in line with a range of other studies on business daily return trip accessibility (Andersson and Karlsson 2004: 293; Rosik, Stępniak and Komornicki 2015: 140 for 'international' trips; BAK Basel Economics AG 2007: 44 for meetings and trade fairs).

Weaknesses of the potential method lie in the interpretability and communicability of its outcomes as the resulting values are dimensionless and meaningful only in reference to other values (Geurs and van Wee 2004: 134), which is why we normalise all values on the highest value of 2020 (= 100). Particular attention must be paid to the zone-internal travel time at the origin location, which is known as the 'self-potential' problem (Geertman and Ritsema Van Eck 1995: 71). Simply using the unweighted mass of the origin would lead to an overestimation of local opportunities. For this paper, we follow the method of Stępniak and Jacobs-Crisioni (2017) by calculating for each region the average weighted distance to the main station from each point of the 1x1 km Global Human Settlement Layer population grid of 2015, the latest year available (European Commission 2019), to account for differing internal population distributions. Attention must also be paid to the spatial extent of the model. The accessibility of a region can be underestimated if neighbouring regions with a high number of opportunities remain unconsidered due to a fixed cut-off, e.g. at a national boundary. This requires defining the system's boundaries in a way that is relevant to the research question. Hence, we included a buffer zone of four hours travel time around Germany in our analysis, since all neighbouring countries are part of the Schengen Zone and rail travel is mostly frictionless.

3.4.2. Degree centrality

Even though seamless travel chains and scheduled interchanges are becoming more important and widespread, the number of other regions that can be reached directly – without a change of trains – can still serve as a locational factor, rather than the number of contacts that can be reached in a certain time. For example, Florida (2017) highlights the importance of the number of destinations that can be reached with a direct flight for a city's economic development. Likewise, Seydack (2015) reports a similar location choice by firms regarding rail connectivity; in Germany's case, showing that firms might value the availability of direct connections to certain important centres, such as Berlin, higher than travel time. Changeovers induce uncertainty in a travel chain and pose a disadvantage particularly for occasional users. As a second accessibility measure, we hence determine the number of other regional centres that can be reached directly without changing trains from a regional centre. For the selection of regions and centres considered for this step, see secion 4.3. In graph theory, this measure is one of the most basic features of a graph and called 'degree' (Barthélemy 2011: 6) or degree centrality (eq. 3-2),

$$D[i] = \sum_{j\, \in G-\{i\}} A_{ij} \qquad \text{(eq. 3-2)}$$

where D[i] is the degree centrality of location i, and Aij is defined as 1 if i and j are connected, 0 otherwise. The analysis of degree centrality is limited to the German rail network without the buffer zone.

3.4.3. Dataset

The paper analyses accessibility changes on a regional scale, for reasons of data availability and clarity. We define 'regional' as functional city-regions identified by commuter catchment areas of typically less than 45 minutes one-way, and hence common labour markets and daily activity spaces for most of their inhabitants (Antikainen 2005; Blum, Haynes and Karlsson 1997). Since HSR is primarily an inter-regional transport mode, there is usually not more than one station per region, which leads super-regional accessibility changes (not levels) to be rather uniform within such functional regions, despite differing local transport connections. The spatial base units of our analyses are 266 functional city-regions ("Stadt-Land-Regionen") developed by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR 2017b). They are homogenous, area-covering, and non-overlapping areas free of exclaves, based on functional relations between urban cores and their hinterlands. This avoids difficulties arising from the heterogeneous definition of administrative areas even of the same hierarchical level between the German federal states. Within the four-hour buffer zone, we use an additional 209 NUTS-3 areas as approximation of functional urban areas, which are of a similar extent.

For each functional urban area in Germany and each NUTS-3 region in the four-hour buffer zone, a main station was defined based on the highest number of departures per day or, where this was ambiguous, based on centrality and importance in the local context. All regions were served by rail in all years of analysis, however, in some cases the main station changed over time (e.g. Flensburg). The dataset contains the fastest travel times of all regular train connections between neighbouring main stations, based on current timetable data obtained by automated and manual web research (DB 2020) for 2020, and the travel times contained in the current second draft version of the "Deutschland-Takt" project for 2030 (BMVI 2019; Grahnert 2020). A connection is considered 'regular' if it runs at least once every two hours over a period of eight consecutive hours on a typical working day. In very few cases, connections with a lower frequency than once every two hours were included, otherwise, a region would be totally unconnected. If the fastest connection between two main stations required an interchange in a station not included in the dataset, this station was added but received no weight. This resulted in a network of 817 nodes and 1350 edges in 2020, and 844 nodes and 1405 edges for 2030. For methodological reasons, we had to resort to a single penalty time for stops at stations as well as interchanges at stations. For both, two minutes was assumed, since connections at nodes are increasingly seamless and timed. We also do not apply a penalty for station access and egress, since there currently are no security checks at stations and passengers can show up shortly before their train departs. When interpreting the results, one has to consider that these represent very optimistic assumptions. The results should therefore be understood as the theoretically optimal usage of the infrastructure's potential. Since this bias applies to all connections and for both points in time, comparisons across regions and time are still possible. For the degree centrality, there were cases where the long-distance connections of a region are distributed across several stations rather than a single main station (e.g. Jena). In these cases, the connections of all relevant stations were added to derive one measure for regional connectivity.

3.4.4. Limitations

The accessibility indicators used here are not free of limitations. First, the accessibility value of one node is attributed to the whole region. This generalisation can produce unrealistic results, as some parts of the region might be less accessible than the main city (Gutiérrez, González and Gómez 1996: 237). Using homogenous functionally defined regions can mitigate this shortcoming to a certain degree. Second, frequencies of connections are only implicitly included in the model, while in practice they can be a main determinant of attractiveness of a train connection. We see better integration of frequency, e.g. through the consideration of average waiting time in the potential accessibility indicator, as a way to improve the model further in the future. Data limitations in our case also prevent a more accurate modelling of changeover times, which would be desirable. Lastly, the dataset is timetable-based, i.e. does not consider delays, which we assume occurs evenly across the network.

3.5. Results

Figure 3-1 and Figure 3-2 show two measures of regional rail accessibility: the potential accessibility of population by rail (choropleth) and the degree centrality, i.e. the number of regions that can be reached without changing trains (points), for each of the 266 functional urban regions in Germany for 2020 and 2030, respectively. Table 3-2 contains an overview of the most and least accessible regions in terms of population potential and Table 3-3 presents a list of the regions with the highest degree centrality in the railway network, in 2020 and 2030. Potential accessibility has been normalised to the highest value of 2020, with Köln as 100.

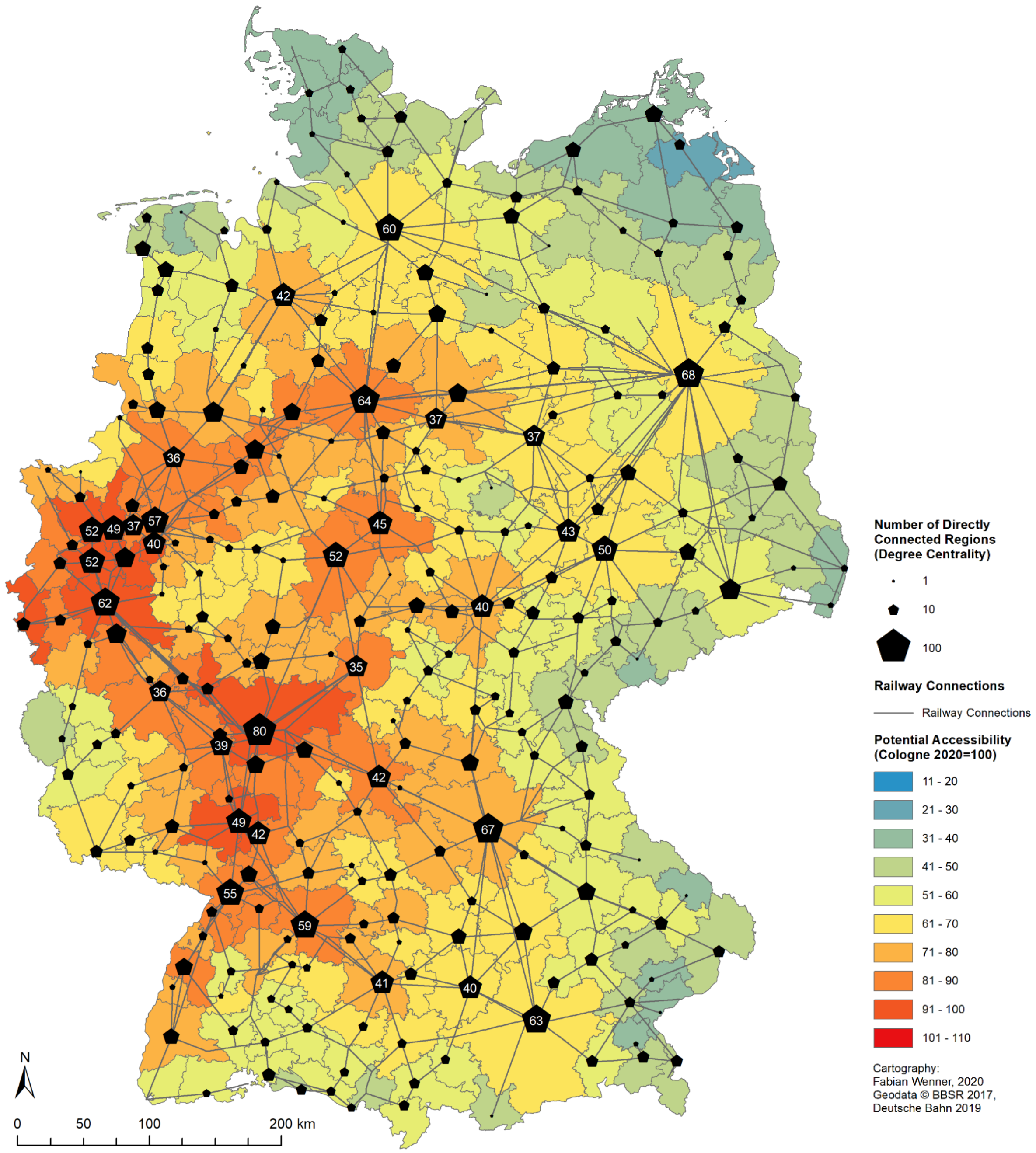

Figure 3-1: *Regional rail accessibility in Germany, 2020*

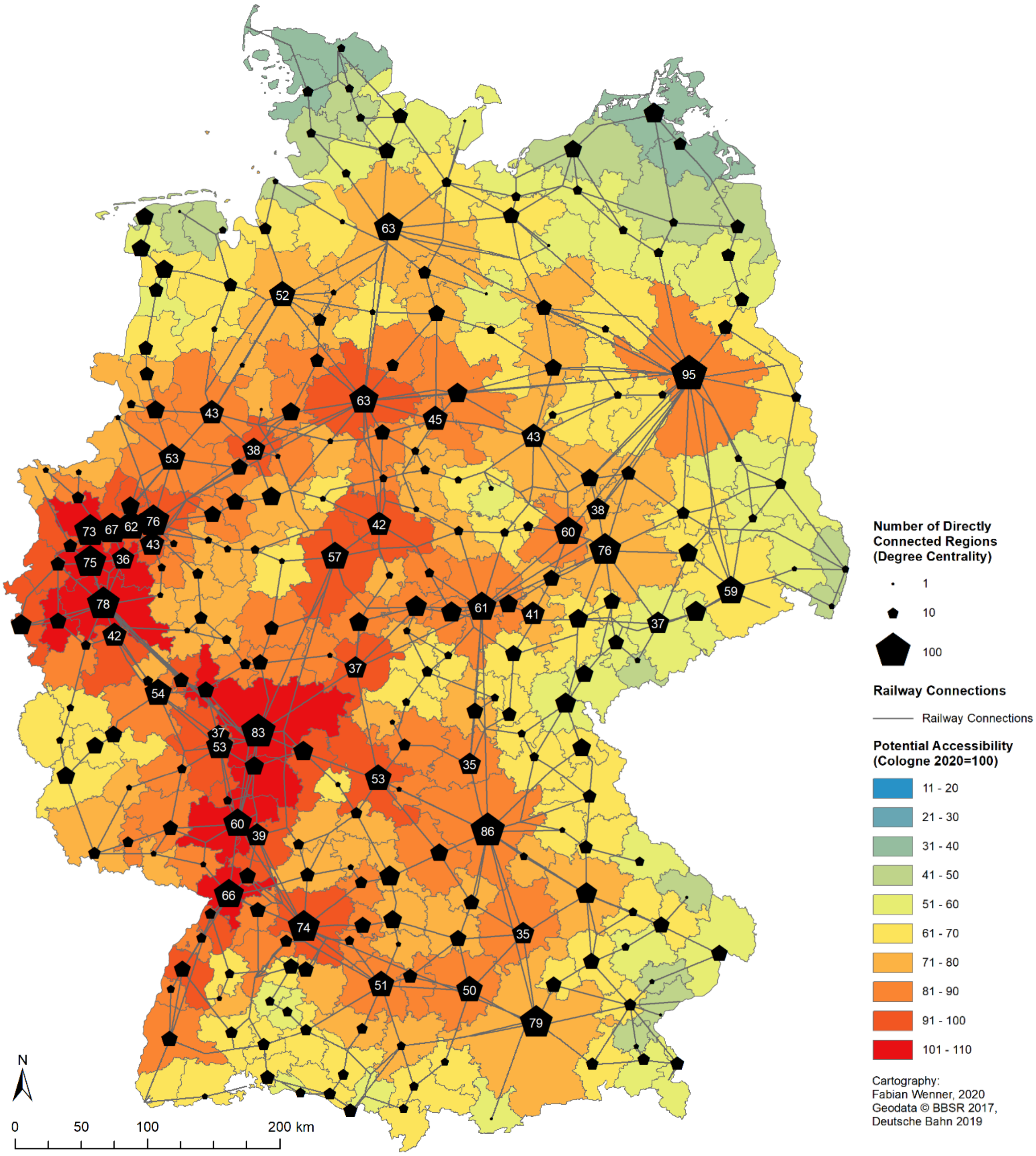

***Figure 3-2**: Regional rail accessibility in Germany, 2030*

2020			2030		
Nr	**Region**	**Accessibility**	**Nr**	**Region**	**Accessibility**
1	Köln	100.00	1	Köln	108.49
2	Frankfurt am Main	97.29	2	Frankfurt am Main	108.31
3	Düsseldorf	96.15	3	Mannheim	106.18
4	Mannheim	95.14	4	Düsseldorf	104.07
5	Duisburg	94.52	5	Wuppertal	102.69
6	Wuppertal	93.92	6	Ludwigshafen	102.67
7	Ludwigshafen	92.04	7	Darmstadt	102.66
8	Aachen	91.74	8	Duisburg	102.14
9	Essen	91.59	9	Karlsruhe	100.53
10	Limburg a.d. Lahn	90.71	10	Limburg a.d. Lahn	100.06
…	…	…	…	…	…
262	Husum	33.36	262	Aurich	40.93
263	Zittau	32.81	263	Flensburg	39.40
264	Flensburg	31.90	264	Husum	38.50
265	Stralsund	30.17	265	Greifswald	36.67
266	Greifswald	28.78	266	Stralsund	36.47

***Table 3-2**: Regions in Germany with the highest and lowest potential accessibility by rail, 2020 and 2030*

2020			2030		
Nr	**Region**	**Degree Centrality**	**Nr**	**Region**	**Degree Centrality**
1	Frankfurt am Main	80	1	Berlin	95
2	Berlin	68	2	Nürnberg	86
3	Nürnberg	67	3	Frankfurt am Main	83
4	Hannover	64	4	München	79
5	München	63	5	Köln	78
6	Köln	62	6	Dortmund	76
7	Hamburg	60	=	Leipzig	76
8	Stuttgart	59	8	Düsseldorf	75
9	Dortmund	57	9	Stuttgart	74
10	Karlsruhe	55	10	Duisburg	73

***Table 3-3**: Regions in Germany with the highest degree centrality in the rail network, 2020 and 2030*

The general pattern of gravitational rail accessibility in 2020 can be interpreted as a section of the "blue banana" model of population distribution in Europe, with a zone of high accessibility along an arc from North-Western Europe and the UK to Northern Italy along the Rhein river, and relatively lower accessibility further away from it, broadly confirming previous studies on rail accessibility in Europe (BAK Basel Economics AG 2007: 16; European Commission 2016), and Germany in particular (Evangelinos, Hesse and Püschel 2011). This highlights the relative strength of the population component in the potential accessibility indicator, and hints at a relatively uniform standard of railway infrastructure. However, several offshoots from this corridor of high accessibility can be seen, which radiate out eastwards from Frankfurt and the Rhein-Main area along different rail corridors. Greifswald in North-Eastern Germany is the region with the lowest rail accessibility in terms of population potential, which is due to its remote position in the infrastructure network and the low population density in the area. Compared to road accessibility, rail accessibility is much more concentrated and discontinuous but infrastructure investments particularly in HSR can have a stronger influence on the distribution (Spiekermann and Wegener 2006: 16).

The general pattern in 2030 looks similar. Köln is the region with the highest accessibility of population by rail in both years, with Frankfurt close behind. Accessibility is a rather inert locational factor that takes time and significant infrastructural effort to be changed. Nevertheless, there are several interesting shifts in the details. With regards to potential accessibility of population, a stronger polycentric pattern in central Germany seems to emerge. It can also be seen from the list that a slow shift of the gravitational centre from the Northwest towards the Southwest can be observed: Regions in the South (particularly Mannheim, Ludwigshafen, and Karlsruhe) have moved up in the list or appear for the first time among the 10 most accessible regions, while the post-industrial regions of the Rhein-Ruhr area could not gain accessibility to a similar degree. Since we have held population constant at 2020 levels, this effect is solely due to differentiated rail infrastructure improvements and service changes. Different peripheral regions in the North remain at the lower end of the scale, despite small gains and some exchanges in places. Zittau, in the very East, no longer appears in the last five places. Regarding degree centrality, Berlin instead of Frankfurt is now the region with the most direct connections.

Figure 3-3 and Table 3-4 display the absolute changes of potential accessibility of population by rail for regions in Germany between 2020 and 2030, as well as the change in degree centrality.

Potential Accessibility of Population			**Degree Centrality**		
Nr	**Region**	**Accessibility Change**	**Nr**	**Region**	**Centrality Change**
1	Weißenburg i.Bay.	+16.43	1	Chemnitz	+30
2	Eisenach	+15.08	2	Jena	+27
3	Ulm	+15.00	3	Freiberg	+27
4	Biberach an der Riß	+14.84	4	Berlin	+27
5	Erfurt	+14.58	5	Leipzig	+26
6	Donauwörth	+14.58	6	Dresden	+25
7	Darmstadt	+14.56	7	Bitterfeld-Wolfen	+25
8	Memmingen	+14.50	8	Bochum	+25
9	Günzburg	+14.31	9	Düsseldorf	+23
10	Ravensburg	+14.22	10	Wiesbaden	+22
…			…		
262	Meschede	+3.40	262	Wittenberg	-5
263	Brilon	+3.34	263	Wismar	-5
264	Korbach	+3.30	264	Celle	-6
265	Albstadt	+2.84	265	Cottbus	-7
266	Bremerhaven	+2.61	266	Lüneburg	-9

***Table 3-4**: Regions in Germany with the greatest and smallest absolute increase in potential accessibility of population by rail and the strongest increase and decrease degree centrality in the rail network, 2020-2030*

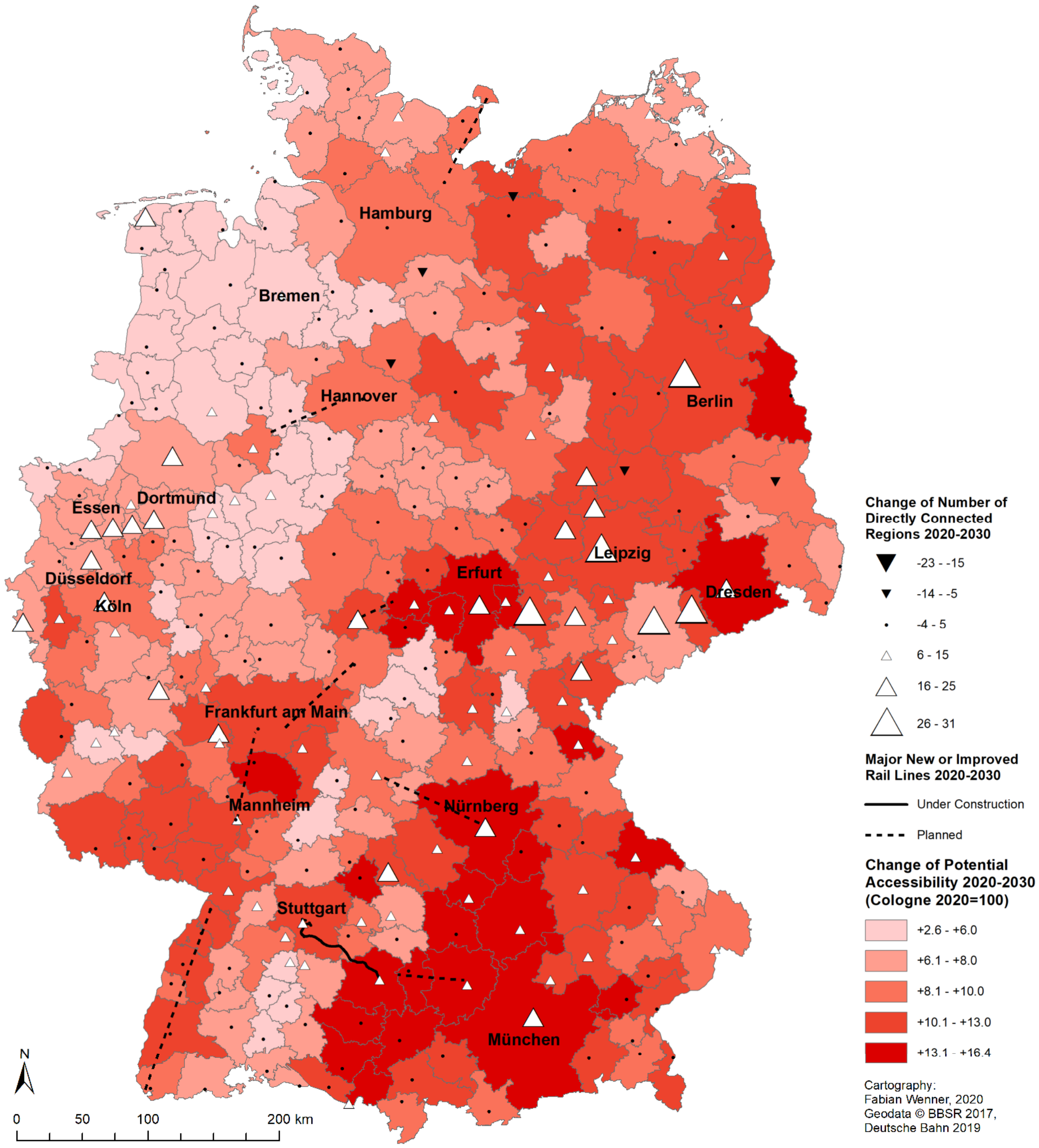

Figure 3-3*: Absolute change of regional potential rail accessibility in Germany between 2020 and 2030*

Absolute regional accessibility gains are spread between 2.61 and 16.43 index points, with Köln (2020) set as 100, underlining significant accessibility gains in some regions. These gains are not distributed evenly. At least three different causes for strong accessibility gains can be identified:

- Several regions profit from new high-speed rail infrastructure, either when they are located directly along or at the end points of new lines (e.g. Ulm, Darmstadt), or when they are located in the wider reach beyond a new line (e.g. Eisenach, Erfurt).
- In several cases, the upgrade and acceleration of conventional infrastructure rather than new high-speed rail infrastructure result in similar accessibility gains (e.g. Biberach an der Riß, Ravensburg, Memmingen), even though there is an overlap with wider HSR gains in some cases.

- In other situations, accessibility gains are merely due to service improvement, particularly the (re-) introduction of stops by long-distance services in regions only served by local and regional trains (Weißenburg i. Bay).

In terms of an overall pattern, it becomes clear that most of the accessibility gains are located in the Southern and Eastern parts of the country, while the Northwest in particular seems to gain little from the rail projects of the current Federal Transport Infrastructure Plan and the "Deutschland-Takt." This is due to the alignment and location of new infrastructure as well as service improvements, which seem to be concentrated in two larger regions: the economically more prosperous and growing metropolitan cores of Southern Germany as well as the lagging Eastern states. This pattern continues an already ongoing longer development trajectory regarding rail infrastructure and accessibility (Wenner and Moser 2020). The geography of accessibility gains also transcends the core-periphery or urban-rural dichotomy. Among the regions with the strongest gains are urban cores (e.g. Erfurt) as well as more peripheral and rural areas (e.g. Ravensburg), while the smallest gains accrue in 'inner peripheries' such as the Sauerland (Brolon, Meschede, Korbach) but also more urban regions (Bremerhaven).

Similar spatial patterns can be observed with regard to degree centrality where the highest gains of directly connected regions occur in the southern part of Eastern Germany (Chemnitz with 30 more regions that can be reached without a change of trains), Berlin, and to a lesser degree areas across Southern Germany. In addition, the Rhein-Ruhr area stands to benefit, while several regions in Northern Germany lose direct connections to other regions. This is largely due to service changes rather than infrastructure improvements. The 2030 plans contain the reintroduction of several long-distance services, e.g. along the central East-West corridor as well as several tangential routes, which improves their direct connections but not necessarily travel times. This change clearly puts Berlin in a more favourable position, (re-) asserting its role as the capital city also in terms of transport. Despite these changes, the focus of the "Deutschland-Takt" measures is to improve interchanges at stations, reducing the importance of direct connections.

Relative changes are distributed differently than absolute changes. Surprisingly, HSR lines mostly seem to induce only average gravitational accessibility increases on the local level. The strongest accessibility gains occur in peripheral regions of Southern and Eastern Germany without new HSR lines. The base effect of an already high endowment of accessibility by rail in most metropolitan cores in the Western part means that – even though new HSR lines are mostly aligned to them – they cannot gain as much in relative terms as the peripheral regions. These disproportionate gains in peripheral regions mainly result from minor improvements of conventional rail infrastructure and service improvements there, which shows that smaller investments can have a spatially widespread impact where the starting level is low. Nevertheless, part of the improvements in peripheral areas are also due to the network effects of HSR, by which travel time reduction effects spread to a wide catchment area beyond the actual lines, and the number of beneficiaries in metropolitan cores is larger.

Figure 3-4 displays the changes in rank position of regions regarding potential accessibility of population. Repeatedly, it has been argued that for the attractiveness of regions for firms and households, the relative accessibility level might be decisive not at the absolute level (Vickerman 1987: 189). A higher rank position can hence signify greater appeal as a business or residential location. Clusters of high rank position increases can be found in the triangle between München, Nürnberg and Lake Constance, in particular the region of Weißenburg, as well as the corridor of Erfurt-Leipzig-Dresden/Berlin. Again, large parts of Lower Saxony and Eastern Westphalia lose relative attractiveness despite largely constant absolute accessibility levels. This affects, to a large degree, already structurally weak areas.

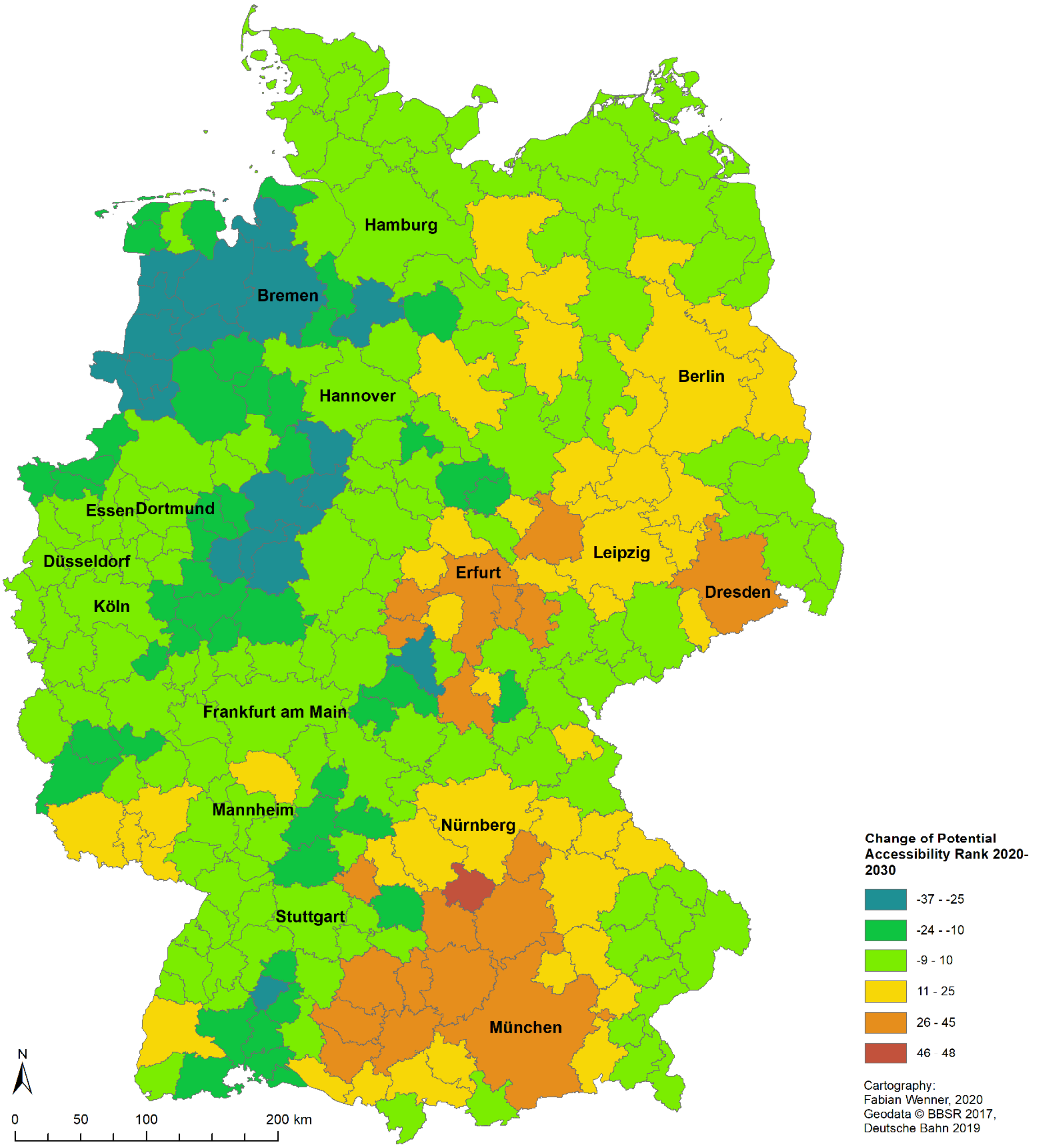

***Figure 3-4**: Change of potential accessibility rank of regions in Germany 2020-2030*

A central question of the paper is whether the planned measures will lead to greater overall balancing or divergence regarding regional rail accessibility. Figure 3-5 shows the regions sorted by their accessibility rank for 2020 and 2030. The diagram shows that apart from the regions with the lowest rank, changes in accessibility are characterised by an overall upward shift rather than a change in the slope of the curve, which would indicate an accessibility increase only for some (core or periphery) regions. The overall shift means however that the least accessible regions are now more accessible relative to the most accessible ones. Accordingly, the Gini coefficient of potential accessibility is slightly reduced from 0.116 to 0.102. The Gini coefficient of degree centrality likewise decreases from 0.412 to 0.395, which signifies a more balanced distribution of accessibility and direct connections across the population. In a similar vein, the so-called Accessibility Dispersion (AD) index used to evaluate the impact of transport infrastructure development on territorial cohesion (Ortega, López and Monzón 2014: 18) decreases from 0.212 to 0.190 during the study period. Lower AD values indicate a more balanced distribution of accessibility.

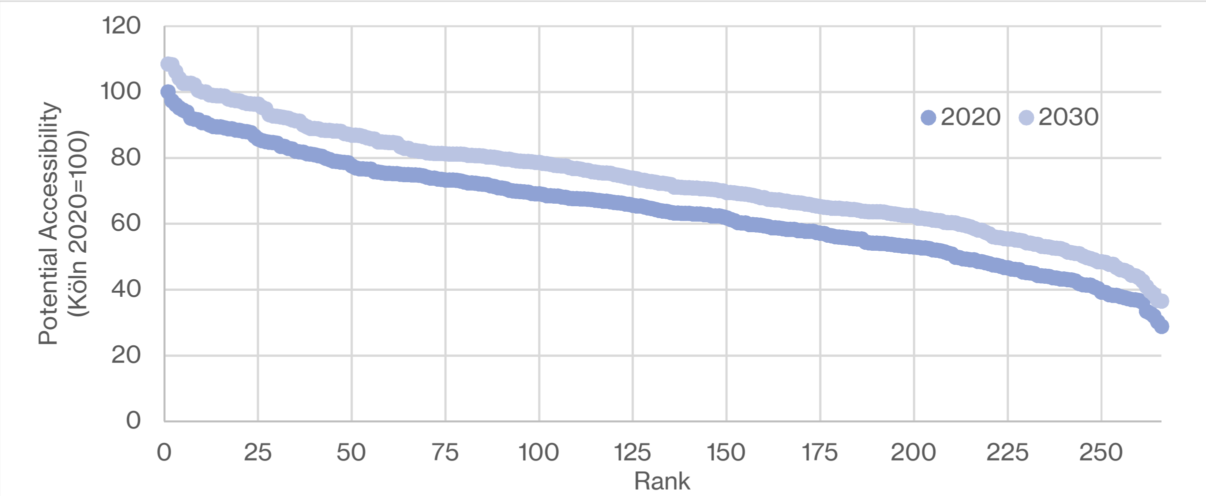

***Figure 3-5**: Regions in Germany sorted by their rank position of potential accessibility of population by rail in 2020 and 2030*

Grouping the functional urban regions according to their demographic and economic development as well as settlement structure types (Table 3-5, Table 3-6) allows for further differentiation. The classification of demographic and economic development is based on six indicators: population development, migration balance, workplace development, unemployment rate, taxable capacity and purchasing power (BBSR 2017c), with the first three having double weighting. The settlement structure types are based on the population share in large and medium-sized cities, population density, and population density without consideration of large and medium-sized cities (BBSR 2017a). It shows that potential accessibility growth is strongest for the regions with the most pronounced demographic and economic change, both positive and negative. It mirrors the observation that planned accessibility improvements are focused on two very different groups of regions, with two different rationales: a demand-driven rationale for the strongly growing, economically prosperous regions mostly in the South and a regional structural policy objective in the economically weaker regions of Eastern Germany. The regions without clear direction of development show the smallest accessibility gains. The base effect of strongly urbanised regions showing smaller relative gains is also visible in Table 3-6. Differences for degree centrality change depending on regional growth or shrinkage are not marked, however a disproportionate growth of degree centrality for "urban" regions can be observed. In relative terms, the "regions with densification tendencies" gain most, which indicates a stronger role of secondary centres in the rail network and a general increase in the number of centres that offer a medium to high level of service (poly-centralisation).

Region Type	**Average potential Accessibility change**	**Average degree centrality 2020**	**Average degree centrality 2030**
Strong growth	+15.6%	21.61	26.56
Growth	+13.6%	15.08	20.65
No clear direction of development	+12.2%	10.86	15.25
Shrinkage	+14.6%	11.37	15.83
Strong shrinkage	+17.8%	7.24	11.76

Table 3-5: *Rail accessibility change of German regions 2020-2030 by regional growth characteristics*

Region type	**Average potential Accessibility change**	**Average degree centrality 2020**	**Average degree centrality 2030**
Region with urban character	+12.3%	21.19	28.36
Region with densification tendencies	+14.9%	10.85	15.42
Sparsely populated regions	+17.2%	8.07	10.50

Table 3-6: *Rail accessibility change of German regions 2020-2030 by settlement structure characteristics*

3.6. Discussion and Conclusion

This paper has analysed the planned development of the rail network in Germany regarding its effects on the spatial distribution of accessibility. We used two accessibility indicators: potential accessibility of population for business trips and direct connections (degree centrality) between functional urban regions as the base unit. We find a mild cohesive development of regional accessibility and a tendency towards poly-centralisation in the German rail network until 2030, if the current plans are implemented. This is the case despite the expansion of High-Speed Rail during this period, which is often argued to exert a 'polarising' influence on space. Instead, the simultaneously planned improvement of interconnections and conventional rail services seems to exert a balancing influence on accessibility equity and helps to spread accessibility gains through HSR to a wider area. Two macro-regions benefit notably from the planned railway projects until 2030: the economically dynamic South and the catching-up East. We interpret this as the outcome of two different rationales that apply to different regions: a demand-driven logic of ensuring "traffic flow" on the one hand, and a deliberative regional development strategy on the other hand. No substantial rail infrastructure improvements have been implemented in the Northwest of Germany during the last decades, which will not change in the next decade as well. An upgrading of the rail line Amsterdam-Hamburg via Groningen and Bremen has been discussed in both the Netherlands and Germany for decades (Evers et al. 1987) but has not been realised yet. Such a project would likely change the picture and drastically improve accessibility in the peripheral, economically less dynamic regions of North-eastern Netherlands and North-western Germany.

However, the development of intra-regional rail accessibility might differ from that of inter-regional accessibility. While in many cases, the closure of local lines has led to a decrease of accessibility on the local level, inter-regional infrastructure is generally not threatened by line closures. A finer-grained analysis was beyond the scope of this paper but could reveal such differences. Current plans for more stops of long-distance trains within regions, e.g. urban sub-centres of larger cities (Karslruhe-Durlach, Hamburg-Bergedorf, Berlin Zoo), regional air-ports (Köln/Bonn, Leipzig/Halle), and smaller network nodes (Bad Oeynhausen, Schorndorf, Schwäbisch Hall-Hessental) point towards such a development, suggesting a greater poly-centralisation of rail accessibility also within regions.

The current regional planning assessment of the BVWP does not use population potential indicators but fixed travel time thresholds to a set of predefined destinations (metropolitan and regional centres, airports, long-distance rail stops) that are assumed equal in function. An analysis similar to the one presented here could posit a more nuanced picture of accessibility deficits and inhomogeneous living conditions. Such benefits are currently not included in the assessment of rail projects, which could improve their utility.

3.7. References

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4. High Speed Rail as Urban Generator? An Analysis of Land Use Change around European Stations

Abstract: The construction of new High-Speed Rail stations often raises expectations for regional and local urban and economic development in the connected places. Accessibility improvements are assumed to increase locational attractiveness for households and companies, motivating municipal decision-makers to allocate land for urban development projects, particularly in the immediate vicinity of new stations. However, most empirical studies call such automatic effects into question. Scientific analyses so far are predominantly case studies of a single station or line – international, comparative analyses are still rare, despite the high number of lines constructed in the last decades in various countries. This paper uses a dataset of 232 stations in 11 countries in Europe to examine how land uses in the surroundings of High-Speed Rail stations have changed before and after construction, by evaluating CORINE land cover data. The analysis confirms and qualifies previous studies, highlighting the importance of local influencing factors, and finding that land use changes are more likely when stations are close to the existing urban fabric and well connected by complementary regional and local public transport. No association with urban development could be found for stations in peripheral locations outside of metropolitan regions.

Keywords: High-speed rail, railway stations, urban development, transit-oriented development

Contributions (CRediT taxonomy): Conceptualisation, F.W.; methodology, F.W.; validation, F.W.; formal analysis, F.W.; investigation, F.W.; data curation, F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W., A.T.; visualisation, F.W.; supervision, F.W., A.T.; project administration, F.W.

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4.1. Introduction

The introduction of High-Speed Rail (HSR) has reinvigorated the role of passenger rail as transport mode and raising expectations of a “second railway age” (Banister and Hall 1993: 161). After the opening of the Shinkansen (1964) in Japan, HSR was soon implemented in Europe as well, where initial national networks have been increasingly connected to an integrated European grid during the past decades. The capacity of HSR to attract substantial ridership and to shift passengers from air and road has been demonstrated in several studies (e.g. Albalate, Bel and Fageda 2015; Givoni 2007) and is generally welcomed from an environmental point of view due to the relatively lower pollutant emissions of rail transport. However, the consequences of HSR for spatial development are less clear. The question has already been addressed early after the opening of the first line (Bonnafous 1987), and has consistently received attention by researchers since, most recently in a special issue of this journal (vol. 27, issue 3, 2019). The question of spatial implications can be discussed on different spatial scales (Sands 1993: 1; Ureña, Menerault and Garmendia 2009: 266; Chen and Hall 2015; Yin, Bertolini and Duan 2015) and with respect to different subjects, such as relocations and commuting (Demuth 2004; Moyano 2016), productivity and agglomeration economies (Ahlfeldt and Feddersen 2018), regional polarisation and hierarchy changes (Spiekermann and Wegener 1996; Puga 2008), tourism (Pagliara, Mauriello and Garofalo 2017; Albalate, Campos and Jimenez 2017), image effects (Willigers and van Wee 2011) and social structure (Moulaert, Salin and Werquin 2001; Albrechts and Coppens 2003). Conventional cost-benefit-analyses of transport infrastructure projects currently only include such “wider effects” to a very limited degree (Blanquart and Koning 2017: 338).

One aspect not fully resolved within this debate is the question whether HSR stations can become generators of new local poles of urban development (Banister and Givoni 2013: 336). Their functions as accessibility providers and intermodal hubs entail certain locational advantages for households and firms, particularly of the knowledge-intensive type, in their immediate surroundings. This demand could – if matched by active planning – lead to the construction of new urban areas around stations. This development can also be a source of revenue-generation for municipalities through active land policy, and change their long-term economic trajectory. While land consumption is a critical component of environmental degradation, some HSR stops in Europe are established at existing stations locations, often with significant reserves of disused railway land and brownfields in their surroundings, available for regeneration. In addition, urban growth around HSR stations represents a form of transit-oriented development, which is at least preferable to car-oriented urban sprawl, from a sustainable urban development point of view.

The question will remain important in future: Numerous new HSR lines are under construction throughout the world, among them 16 more lines with 44 stations in Europe, and numerous further lines are planned. Particularly in the context of the currently discussed post-Corona stimulus packages and the climate crisis, HSR network expansion will likely represent a favoured investment option for governments.

Several examples of new business districts and reinvigorated urban neighbourhoods, but also tendencies of gentrification and displacement, around HSR stations in Europe have been discussed in the literature, such as in the cases of Lille's "Euralille" project (Newman and Thornley 1995; Moulaert, Salin and Werquin 2001), Lyon Part Dieu (Bonnafous 1987; Mannone 1997), and Amsterdam Zuid (Trip 2008; Willigers and van Wee 2011). Together they show that "railway stations have (re-) emerged as prime targets for ambitious urban redevelopment initiatives, and are thus likely to feature prominently in future debates over the ongoing post-industrial, post-Fordist restructuring of cities and regions" (Peters and Novy 2012a: 5).

The often sudden and strong accessibility changes brought about by HSR mean that they represent interesting "laboratory situations" for research. However, most studies so far deal with single HSR stations or lines as cases. Few comparative and international studies exist on land use changes in the immediate surroundings of HSR stations. This article attempts to close this gap by asking the question whether patterns can be observed by analysing land use change in a large number of cases. It aims to supplement case-based studies, which are crucial to identify case-specific local dynamics, which cannot be fully captured with quantitative approaches.

The paper focuses on European stations. European integration means that the political, economic, and demographic framework conditions have become harmonised throughout the continent, facilitating cross-country comparisons. Most lines in Europe are furthermore part of the Trans-European Networks (TEN) policy of the EU. Conditions in the Asian countries, particularly in China, the country with the largest HSR network, differ from those in Europe. New HSR stations in China, for example, are often far outside the traditional city cores and at a greater distance from the conventional rail stations, reducing their appeal for commuters and residential development (Diao, Zhu and Zhu 2017). The scale of intervention and urban development plans around the stations is unmatched throughout Europe. Hence, these case merit a separate treatment, and cannot be included here.

The article is structured as follows: First, the theoretical background for station area development is briefly revisited before an short literature review of previous studies on the topic is presented. Based on this, the following part presents hypotheses and methodology in more detail. The article is based on a database of 232 HSR-related stations that have been constructed in Europe since 1981 or are currently still under construction. The following results section presents a region and station typology based on locational, service, and network characteristics, followed by a descriptive analysis of land cover changes in relation to opening time and station characteristics. CORINE land cover data is used for this analysis step, since it represents a unique Europe-wide dataset that is available in constant quality across the timeframe of the study. Finally, the article discusses the results and presents further avenues for research.

4.2. Theoretical approaches to HSR stations as nodes of urban development

Different theoretical perspectives can be invoked to reason why new urban development can emerge around HSR stations. HSR is primarily an inter-regional transport mode, but it can have consequences on different spatial scales. In an intra-regional perspective, the monocentric urban model (Alonso 1964) represents a useful theoretical base that also serves as backbone of many formal land use/transport interaction models. It posits that different users of space constantly trade off generalised travel costs to a single regional centre with land prices, resulting in a land use pattern of concentric rings sorted by willingness and ability to pay, with commercial uses close to the centre, and residential uses further away. New public transport stations on express lines that are connected to the regional centre become attractive poles for residential suburbanisation, as they combine relational proximity to the centre with (initially) lower land prices. The model can be linked with the theory of "constant travel time budgets", which stipulates that households are willing to invest a certain amount of time per day, usually around one hour, for travel – improved infrastructure hence does not reduce commute times in the long run, but rather leads further suburbanisation and thereby longer commute distances (Zahavi and Ryan 1980; Marchetti 1994). Hence, HSR has the potential to integrate small and medium-sized cities in a metropolitan functional context that were too distant before its construction (Garmendia, Ribalaygua and Ureña 2012: 26; Garmendia et al. 2008: 249) and extend the catchment area and demand for businesses in central locations, but it can also cause suburbanisation.

However, the monocentric model becomes increasingly difficult to apply in today's heterogeneous urban landscapes characterised by differentiating locational demands. Increasingly, 'soft' locational factors become more important than market accessibility, and firms increasingly follow (knowledge-intensive) households rather than vice versa (Glaeser, Kolko and Saiz 2001). In addition, while the growing importance of spatial proximity in a globalising world leads to a concentration of firms in metropolitan regions – and contributes to a "peripheralisation of the periphery" (Hall 2009: 65) – there is a parallel trend of regionalisation within them (Volgmann and Münter 2018). The improved linkage both within and between regions can lead to the emergence of "integrated corridor economies" (Blum, Haynes and Karlsson 1997: 1) and "polycentric mega-city regions" (Hall and Pain 2006) with locational specialisations. HSR can hence contribute to new concentrations of economic activities in peripheral locations within regions, which has been described with the concept of "edge cities" (Garreau 1991: 66; Hall 2009), in a similar vein as this has been discussed in the case of airports ("Airport Cities", "Aerotropolis", …) (Conventz and Thierstein 2014; Appold and Kasarda 2012), while central locations become attractive options for double-income households. Out-commuting (Heuermann and Schmieder 2018: 360), super-commuting (Pütz 2015: 3) and tangential connections, bypassing the local centre, are hence becoming more prevalent.

A relational perspective presents a way to conceptualise these influences on different spatial scales. HSR stations represent nodes in the "space of flows" (Castells 1996), which are often better linked among each other than with their hinterland. Such nodes offer systemic accessibility as a scarce resource. By reducing the transportation costs between two such nodes, HSR contributes to the emergence of “network externalities” (Capello 2000) for firms, that can effectively complement or partially substitute localised agglomeration externalities (Meijers, Hoogerbrugge and Cardoso 2017), particularly for firms in remote areas (Andersson and Karlsson 2004). For example, firms can harness knowledge exchange at fairs and conventions (temporal proximity) to build “global pipelines” in addition to “local buzz” (Maskell, Bathelt and Malmberg 2006). Particularly urban, tertiary sector firms with national and international orientation, such as consultancies (Bonnafous 1987: 135), the information-based economy (Sands 1993: 1) and knowledge intensive firms (Thierstein et al. 2008; Chen and Hall 2011) value the opportunity for a high number of face-to-face contacts and personalised knowledge exchange. HSR facilitates such contacts, and therefore creates an incentive to locate close to the system’s entry points (Lutter and Pütz 1993: 620). This has led Plassard (1994: 44) to describe HSR as “the most sophisticated of the urban transport modes”. Development effects of new rail infrastructure are therefore likely to be concentrated around stations (Vickerman 1997: 35). Particularly, locating close to an urban HSR station can allow firms to profit from both, local agglomeration economies and HSR-generated network economies, especially when HSR also serves as a feeder service to the superordinate air transport system (Givoni and Banister 2006), in turn making the station and those connected to it in short travel time more attractive for households as well.

From an integrated urban and transport planning perspective, polycentric, dense, and mixed-use urban development around public transport stations is generally desirable. Such “transit-oriented development” reduces access and egress times for users, thereby minimising their propensity to use the car, which is beneficial from an environmental and social perspective (Newman and Kenworthy 1989). At the same time, it contributes to the profitability of public transport services. Furthermore, residential areas around stations enable social surveillance (“eyes on the street”), which improves perceived security and makes communities more liveable (Jacobs 1961). Even though such a development might mean the conversion of green space into building land, it is at least considered preferable to urban sprawl that is inaccessible by public transport in the case of growing metropolitan regions (UN Habitat 2009). Hence, rail stations as ‘nodes’ of accessibility should also be considered as ‘places’ for dense, mixed use development (Bertolini 1999). These principles can be applied to local public transport (Caset et al. 2019), but also to high-speed rail stations (Kim, Sultana and Weber 2018: 135).

4.3. Previous empirical findings

For the (first) “age of the railway” around the beginning of the 20th century, a close and lasting relationship between transport accessibility and urban growth has been demonstrated on different spatial scales, such as for cities and towns in Sweden (Berger and Enflo 2017) and the Netherlands (Koopmans, Rietveld and Huijg 2012), and on the neighbourhood-scale in London (Levinson 2007) and within German cities (Bodenschatz 1983). While it is unlikely that rail access can still exert such a strong influence today, in competition with air and road traffic, HSR represents a significant improvement of rail’s competitiveness.

While there is a large number of studies on a regional level, only few studies on the interrelations between spatial development and HSR have so far focused specifically on the local scale.

Empirical findings on the relation between new HSR accessibility and local development are mixed. On the one hand, there are several examples of areas assigned for commercial and residential development around HSR stations that have remained undeveloped. The business parks around peripheral stations in small and medium-sized cities along the first HSR lines in France were generally not successful, even when local stakeholders had keenly anticipated the arrival of HSR (Mannone 1997: 578; Facchinetti-Mannone 2006; Vickerman 2015; Beckerich, Benoit and Delaplace 2019). The ambitious mixed-use new town project of "Valdeluz" near the Guadalajara-Yebes HSR station in Spain has been described as one of the largest real estate failures in the country, paralysed by the economic crisis after 2008 (Bellet 2016: 53). Studies of land value changes as indicators for locational attractiveness have found only weak effects of inter-city rail projects as compared to inner-city rail projects in the case of Berlin, Germany (Ahlfeldt 2012) and Taiwan (Andersson, Shyr and Fu 2010). Authors highlight that other factors are more important for urban development than transport accessibility: "In a society where globally all places are easily accessible, transport no longer structures anything" (Plassard 1994: 63).

On the other hand, a number of studies find evidence for a positive relationship between HSR accessibility and urban development and see HSR stations as a "tool" for urban planning (Ureña, Menerault and Garmendia 2009: 269). Likewise, Bellet, Pilar and Gutiérrez (2016: 193) conclude that the introduction of HSR has been capable of transforming the physical structure of cities, and Garmendia et al. (2008: 257) find that the HSR station, together with the presence of a university, was able to redirect the residential growth of smaller cities along the first Spanish HSR line towards them. In another case study of the new urban sub-centre station of Kassel-Wilhelmshöhe in Germany, Schütz (1997) finds evidence for urban intensification in a 5-10 minutes walking area around the station. Consequentially, he recommends to integrate rail and real estate development (p. 158) and conceptually exploit HSR connections to deliberately close building gaps around stations (p. 114), but also highlights the danger of generating sprawl at peripheral locations (p. 100). In a critical perspective, however, this also poses the risk of gentrification (Albrechts and Coppens 2003: 215). At the same time, station reconstruction in the course of HSR implementation often frees substantial parts of disused railway land in central locations, particularly when stations are relocated.

While at centrally-located stations, development seems to be predominantly residential (Bellet, Pilar and Gutiérrez 2016: 170; Cervero and Bernick 1996) and business-oriented, peripheral stations seem to be more attractive for industrial uses (Coronado, Ureña and Miralles 2019: 438; Beckerich, Benoit and Delaplace 2019: 574). However, almost all authors agree that potential effects are neither automatic nor universal (Chen and Hall 2011: 689). Their materialisation depends on the characteristics of the specific HSR project and further local influencing factors (Bonnafous 1987: 136; Plassard 1994; Givoni 2006: 605; Bellet, Pilar and Gutiérrez 2016: 164).

A detailed analysis and review of academic and "grey" literature on influencing factors on urban development around HSR is provided by Loukaitou-Sideris et al. (2012: 63-65) and Loukaitou-Sideris et al. (2013: 630), who conclude that the degree of embeddedness of a station in the urban context appears to be the most important planning factor for subsequent development, followed by (local/regional) public transit connectivity, good and frequent HSR service, and political intent, aided by good pedestrian access and station architecture, with a lower importance of central station location for peripheral cities. Loukaitou-Sideris and Peters (2020: 436) group these factors into the three types of operational, intermodal, and spatial connectivity. Moreover, the availability of building land, which can also be disused railway areas, can be an important precondition. In addition, there are factors beyond the scope of local planners and policymakers, among them the position of the city in relation to other cities and the metropolitan context, and its general economic endowments, as highlighted for example by the results of Coronado, Ureña and Miralles (2019: 444; 447).

Several of the factors mentioned, particularly the station location or urban embeddedness, are common conflict issues between local actors on the one hand and those with a national and network-based purview on the other, in the context of smaller and medium-sized cities (Bellet 2016: 45; Facchinetti-Mannone 2006: 3; Zembri 1993: 286). In large cities, HSR lines are typically introduced in existing central (terminal) stations with good local public transport connections. In contrast, in smaller cities and rural areas, out-of-town "greenfield" station locations along the straight-line routes between the major cities are typically preferred by the railway infrastructure providers, if any stations are to be constructed at all, as they save both travel time for through-passengers and construction costs. Local actors, on the other hand, typically prefer integrated station locations, particularly if conventional services are discontinued after the opening of the HSR line.

Further influencing factors are the influence of business cycles, image, and car access. The role of business cycles becomes particularly clear in the special case of the real estate crisis in Spain after 2008, which has brought several urban development projects close to HSR stations to a halt (Bellet 2016: 53; Bellet and Santos Ganges 2016: 15; Ribalaygua, Sánchez and de Ureña 2020: 458). It can even be argued that the enormous expansion of HSR in Spain itself followed the logic of the construction boom before. Image effects are described as both a consequence of the connection of a city to the HSR network, and a separate reason for firm (re)locations (van den Berg and Pol 1998; Pol 2002; Willigers and van Wee 2011: 753). In fact, stated preference surveys often reveal that actual usage of HSR is low among firms that consider station proximity important, and find that image effects can outweigh the accessibility effects for location decisions of firms (Delaplace 2012: 282; Eck 2000: 149-153). Similarly, for many firms, car accessibility seems to trump public transport accessibility (Beckerich, Benoit and Delaplace 2019: 588; Demuth 2004: 124; van den Berg and Pol 1998: 496; Wulfhorst 2003: 120-121), and HSR stations are often coincidentally also locations with good access by car.

Several authors also highlight the existence of a significant time-lag (Beckerich, Benoit and Delaplace 2019: 589) between opening of a station and urban development in its environs, with estimates ranging from 5-7 years (Bonnafous 1987: 131) to more than 20 years (Bellet, Pilar and Gutiérrez 2016: 187). At the same time, authors highlight the existence of (speculative) foreshadowing effects, particularly with respect to land prices, after the announcement of the construction of a new line, but before its opening (Demuth 2004: 142; Ribalaygua, Sánchez and de Ureña 2020; Schürmann and Spiekermann 2011: 36).

Most studies so far analyse a single case or line. Methodologically, there is a focus on qualitative and descriptive studies. Quantitative-comparative, ex-post and long-term studies across a larger number of cases and entire networks are scarce (Coronado, Ureña and Miralles 2019: 435; Garmendia, Ribalaygua and Ureña 2012: 30) and often focus on the regional rather than the local scale, with the notable exception of several recent studies with a geographical focus on Spain (Coronado, Ureña and Miralles 2019; Mohino, Loukaitou-Sideris and Urena 2014; Mohíno, Ureña and Solís 2016; Ribalaygua, Sánchez and de Ureña 2020).

This article contributes to the closure of this gap by analysing quantitatively and in a comparative perspective land use changes that have occurred around HSR stations in Europe. We differentiate according to supporting factors identified in this paragraph, time-lags or foreshadowing effects, and between different land use categories.

4.4. **Data and Methods**

A database of 232 HSR stations assembled by the authors serves as the foundation of our analysis. Stations were included in the database if they are located on, or in the direct approach to or from new HSR lines that conform to the widely used definition of HSR as "specially built high-speed lines equipped for speeds generally equal to or greater than 250 km/h", established by the European Union in 1996 (European Council 1996). This represents a substantial change in top speeds compared to the conventional network, with typical speeds of up to 160 km/h, in some cases effectively resulting in a complete reconstruction of the rail network. Upgraded lines, which are also mentioned in the EU definition, were explicitly excluded from this analysis, since upgraded lines typically cause only minor incremental accessibility changes, mostly at existing stations. Nevertheless, the findings of this article might apply to these lines as well, albeit in attenuated form. HSR is hence understood here as a certain type of infrastructure, that allows a range of services to operate on it (fast intercity services, but also regional and/or freight services), and not as a type of train service – irrespective of speed – as in other studies (e.g. Delaplace 2012; Heuermann and Schmieder 2018), as the study focuses on travel time changes, not quality changes, as main impulse. The analysis includes lines already in service as well as under construction, but not those that are only in the planning stage.

4.4.1. Station Typology

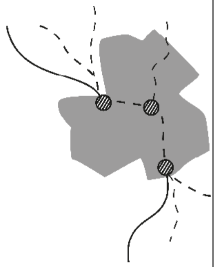
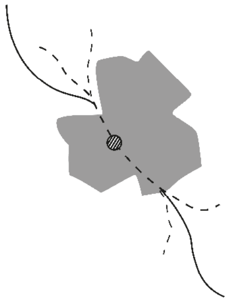
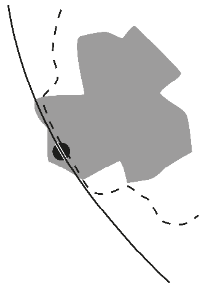
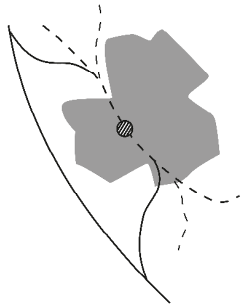
Schematic Illustration				
Type	**Type 1** Metropolitan Multi-Hub	**Type 2** Traditional Urban Hub	**Type 3** New Node	**Type 4** Bypass/Branch
No. of stations	2 or more	1	1	1
Population	Very high	High	Medium	Medium
Typical location(s) of station(s)	Central, existing stations –Terminal or through stations; Airport and trade fair stations	Central, existing station –Terminal or through station	Central or urban fringe, existing station, sometimes marginally shifted	Central, existing station
Integration with conventional long-distance, regional, and local services	Strong	Strong	Strong	Strong
Stopping HS services	All; Sometimes dedicated stations for certain destinations	All	Some	Some
Accessibility	High by public transport, low by car	High by public transport, low by car	High by public transport and car	High by public transport, reasonable by car
Cost	High	High	Medium	Medium
Examples of HS stations	Berlin, Paris, Milano	Würzburg Hbf, Córdoba, Bordeaux-St-Jean, Liège-Guillemins, Bologna Centrale	Montabaur, Ciudad Real, Ashford International	Poitiers, Coburg, Breda, Arezzo, Lleida Pirineus

***Table 4-1**: Seven types of regions by HSR connection*

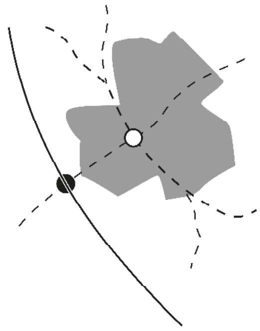
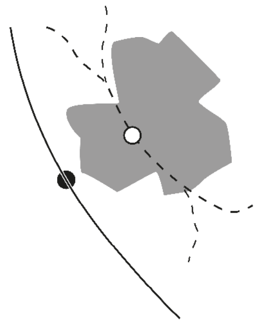
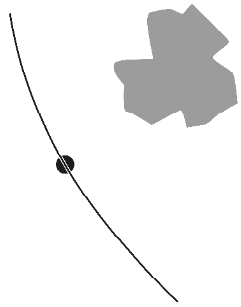
Schematic Illustration			
Type	**Type 5** Distributed Services	**Type 6** Peripheral Replacement	**Type 7** Regional Halt
No. of stations	2	2	1
Population	High to Medium	Medium	Low
Typical location(s) of station(s)	Central, existing and peripheral, new station	Central, existing and peripheral, new station	Peripheral, new station
Integration with conventional long-distance, regional, and local services	Medium; Regional services mainly at central station, requires interchanges	Weak; Regional services at central station only. No rail connection between peripheral and central station	None
Stopping HS services	Some, either distributed between central and peripheral station, or all at peripheral station	Some, generally only at peripheral station	Few and infrequent; sometimes dedicated slower HS services to a small number of destinations only
Accessibility	Peripheral station: reasonable by public transport, high by car	Peripheral station often not accessible by public transport, high by car	Often not accessible by public transport, reasonable by car
Cost	Medium	Low	Low
Examples of HS stations	Champagne-Ardenne TGV, Siegburg/Bonn, Reggio Emilia AV Mediopadana, Køge Nord	Guadalajara-Yebes, Limburg Süd, Le Creusot	TGV Haute-Picardie Villanueva de Cordoba-Los Pedroches, Kinding (Altmühltal)

***Table 4-1** (cont.): Seven types of regions by HSR connection*

For the analysis, stations were classified into seven categories, based on the assessment of the data gathered as well as previous classifications used in literature, taking into account the number of stations within a city-region, their location with regard to the city they serve, their integration with the conventional, regional, and local services as well as the number of stopping HS services in the region. The greater number of cases allows and necessitates a more differentiated classification than in similar previous studies. The classification used here is based on the regional typology of HSR connections developed by Troin (1997: 41), which captures most dimensions identified in the previous section. As this classification is by regions, not by stations, the 232 stations of this study were allocated to one of 187 city-regions, some regions being served by more than one HSR station. The Functional Urban Areas (FUAs) of the 2018 EU Urban Atlas (EEA 2020) were used as a base regions for this step. For a detailed overview of the region types, see Table 4-1. While this categorisation allows an unambiguous attribution of most cases, there is a small number of cases in which an attribution was made based on the most dominant local characteristics by the authors.

4.4.2. Land Use Change

The aim of this study is to assess the degree of land use change around HSR stations. To monitor changes in land uses, we utilise the CORINE land cover (CLC) data by the European Copernicus Programme (EEA 2019). CLC data is based on the evaluation of high spatial resolution satellite images, assisted by topographic maps, ortho-photos and ground survey data. It grades land uses into 44 classes (identified by three-digit codes) belonging to five broad categories: artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands, and water bodies. For this analysis, conversions from the "agricultural" and "forest and semi-natural areas" categories into the "artificial surfaces" category are most relevant, particularly conversions to the sub-classes of "continuous" and "discontinuous urban fabric" (111, 112), "industrial or commercial units" (121), as well as "green urban areas" and "sports and leisure facilities" (141, 142). The subclasses of "Mine, dump and construction sites" (13x) are not considered here, since the locational demands of primary industries are assumed to be not strongly influenced by HSR. Construction sites are excluded as 'preliminary' land use status to avoid double-counting. Furthermore, land used for transport purposes, particularly "road and railway land" (122) is not measured at the outcome level as this would be self-referential, but also "port areas" (123) and "airports" (124), as their development is typically not market-driven on a local scale.

While there are other, more precise land use surveys in some European countries, a unique advantage of CLC data is that it is available for a long time span and similar quality across all European countries. The first instance was produced in 1990, followed by a 10-year gap until 2000. From 2000 on, CLC data has been published in 6-year intervals, i.e. 2006, 2012, and 2018. In addition to the 'static' geospatial land cover data for each year, a land cover change layer has been published for each interval. The static layer has a relatively coarse resolution, with a minimum mapping size for any land cover of 25 ha, reducing its usability for small-scale urban analyses (Siedentop and Meinel 2004: 8), but the change layer has a resolution of 5 ha (EEA 2011: 4). With respect to the total urban land area and the area converted to urban land, CLC data has been found to be relatively reliable (Diaz-Pacheco and Gutiérrez 2014: 243) for the 2000 and 2006 versions. However, changes to the urban sub-classes within the artificial surfaces category are overestimated, as they include small polygons that in reality change to other urban uses (p. 254). The existence of a longer time-series also allows the analysis of a potential reverse causality from urban development to the construction of a new HSR station.

This study focuses on land cover changes in the immediate surroundings of stations, even though, as described previously, a HSR station can theoretically affect land uses in the entire city or city-region that is served by it. As "station surroundings", this study assumes a concentric buffer zone of 1500 meters. Even though isochrone-based accessibility measures have many advantages over buffers, this study applies a buffer to keep the area under surveillance constant over time. Using an isochrone would lead new roads to increase the study area and bring more areas within reach of the station, even though land cover might not have changed, leading to overestimation of changes (even though new access roads can also be a developmental consequence of HSR stations). The relatively large buffer zone is based on the assumption that HSR, as the highest-tier category of rail based transport, justifies higher efforts to access it than regional or local train stations, for which radii between 500m and 1km are typically assumed (e.g. Wulfhorst 2003: 29), and that new forms of local access mobility, such as (shared) (e-)bikes, scooters etc., significantly increase the tolerable access radius. Under these assumptions, it is compatible to the threshold of 10 to 15 minutes access time to the station (Schütz 1997; Willigers and van Wee 2011: 753).

Generally, land use change as an indicator has been less frequently investigated than other indicators in studies of transport infrastructure expansions, such as population density or land value change (Kasraian et al. 2016: 781, 788), and mostly for dynamics within city-regions. Hence, the analysis of inter-regional transport infrastructure on land cover change presents a research gap. The only published study that uses CORINE data in combination with HSR known to the authors is Shen, de Abreu e Silva and Martínez (2014). The study analyses land cover change in Madrid through HSR and finds that it "contributes positively to the development of artificial land covers", taking into account both HSR travel time and station access time (p. 192). It also finds that the existing station neighbourhood, especially the character of the adjacent cells, plays an important role in land cover change (p. 194).

4.5. Results

The first descriptive analyses use the regional types as evaluation criteria. The number of regions analysed is 187.

4.5.1. Development of station location strategies

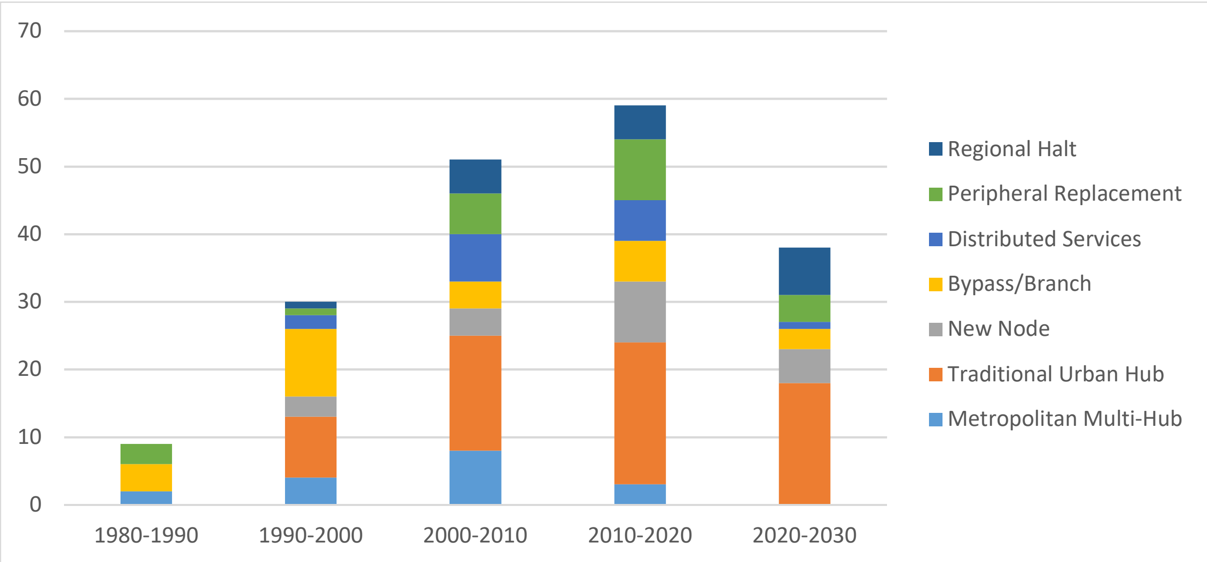


***Figure 4-1**: Number of regions newly connected to HSR by decade of line opening and connection type*

Figure 4-1 shows the number of regions connected to HSR by decade, according to their connection type (see Table 4-1). It can be seen that in each decade, the number of regions in Europe first connected to HSR has grown, while the decade between 2020 and 2030 will see a decrease of newly connected regions, at least if only projects already under construction are considered. Compared to the initial years, there is now a high share of "conventional" inner-city station locations ("Metropolitan Multi-Hub" and "Traditional Urban Hub"), which account for more than 50% of all HSR stations, but a significant portion of newly constructed stations continues to be peripheral with few or no connections to the existing conventional rail network or local public transport ("Peripheral Replacement" and "Regional Halt"). 148 of the 187 regions had been served by both long-distance and regional rail before, 27 regions had only regional rail connections, and 12 regions had no rail connections altogether before HSR.

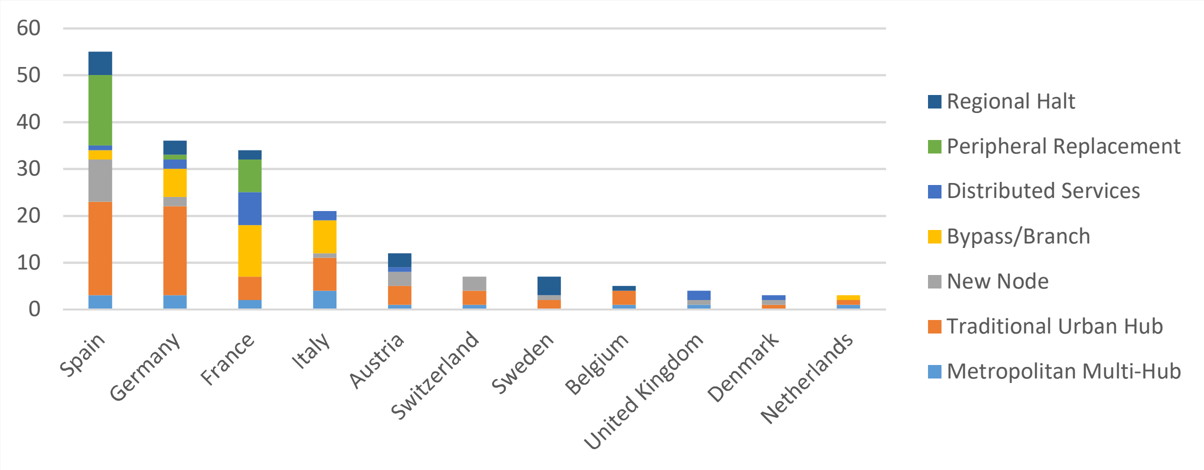
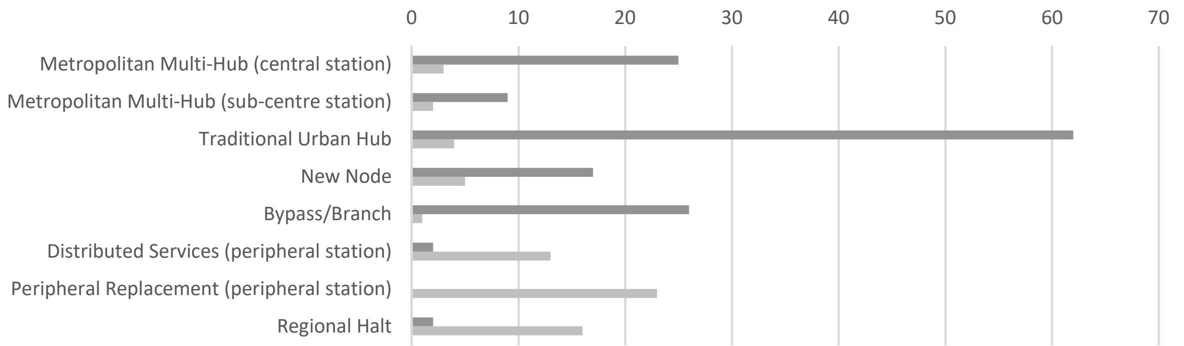


***Figure 4-2**: Total number of regions connected to HSR 1981-2020 by country and connection type*

Figure 4-2 shows the distribution of HSR-connected regions, by type, over the European countries. HSR implementation in Europe started in France with the Paris-Lyon line (1981), followed by Germany (1991), Spain (1991) and Italy (1992). These lines were later connected to form a European network that also extends to the UK and the Benelux countries, while isolated stretches exist in Austria, Denmark, Sweden, and Switzerland. The high number of HSR regions in Spain is striking and shows the enormous scale of its recent network expansion. In France and Germany, there is a similar number of regions directly connected to HSR infrastructure, despite France's longer HSR network, pointing to the higher station density in polycentric Germany. Differences in station policy by political and geographical characteristics become obvious in the diagram: Rather monocentric countries with a lower population density on the countryside (France, Spain) feature less inner-city stations than polycentric countries (Germany, Italy). Recent studies point to a rethinking of this policy in France and Spain, however, which can be interpreted as a sign for a growing recognition of the potential of HSR stations as a tool for urban regeneration (Ribalaygua and Perez-Del-Caño 2019: 597). Such a change had been long desired by experts as more passenger-friendly (e.g. Zembri 1993: 295; Troin 1997: 41), particularly in the case of a separation of local and long-distance transport at two different locations, with weak or none public transport connections between them (Mannone 1997: 92; Bellet 2016: 52). The fact that HSR infrastructure in Spain is generally incompatible with the conventional network (different track width) also plays a role for the low number of integrated station locations.

The following analyses are concerned with individual stations instead of regions. In case of multiple stations within a region, the classification was further differentiated into "centre", "sub-centre" and "airport/trade fair" stations in the case of "Metropolitan Multi-Hub" regions (type 1), and into "central" and "peripheral" (also called 'gare-bis' or 'parkway' stations in other studies, e.g. Zembri (1993: 285); Facchinetti-Mannone (2009)) stations for the regional types “Distributed Services” and “Peripheral Replacement” (types 5 and 6), expanding the seven regional types to eleven station types. However, due to the low number of cases and the largely missing HSR services, the central stations of the latter types are omitted from the further steps, as well as airport and trade fair/theme park stations in multi-hub regions due to their special conditions. This reduces the number of analysed stations to 210.

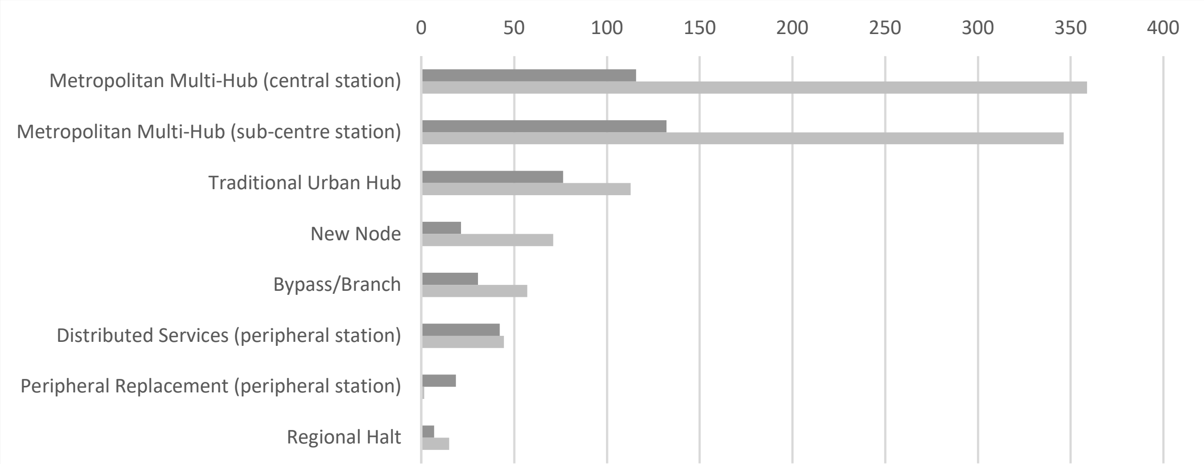


	Regional Halt	Peripheral Replacement (peripheral station)	Distributed Services (peripheral station)	Bypass/Branch	New Node	Traditional Urban Hub	Metropolitan Multi-Hub (sub-centre station)	Metropolitan Multi-Hub (central station)
Existing	2		2	26	17	62	9	25
New	16	23	13	1	5	4	2	3

Existing New

***Figure 4-3**: Locations of HSR stations by station type*

While inner-city HSR stations are typically at locations where a conventional rail station existed before, the peripheral and exurban stations in regions of type 5-7 are usually at entirely new locations (Figure 4-3). In the case of stations at new locations (66), in 12 cases the station was shifted entirely from its previous location, in 37 cases some of the services, particularly long-distance, were relocated, while other services remained at the previous location, and in 17 cases no service changes occurred at the previous location.



	Regional Halt	Peripheral Replacement (peripheral station)	Distributed Services (peripheral station)	Bypass/Branch	New Node	Traditional Urban Hub	Metropolitan Multi-Hub (sub-centre station)	Metropolitan Multi-Hub (central station)
Long-distance services	6.9	18.6	42.3	30.5	21.4	76.5	132.2	115.8
Regional Services	15.1	1.6	44.5	57.0	71.2	112.8	346.3	358.9

Figure 4-4*: Average departures per day by station type*

Figure 4-4 shows the average number of departures per day for long-distance and regional services for the different station types and visualises the strong differences in service quality.

4.5.2. Land cover change

Analysing land cover changes in the station surroundings, we found a total of 9090 ha of land use conversions during the study period. Conversions among different classes of artificial land play a subordinate role in our analysis (about 6% of all land cover changes) compared to conversions from agricultural and forest to artificial use. Conversions within artificial land classes are almost always intensifications (discontinuous to continuous urban fabric, urban green space to urban fabric, etc.).

For the following analytical steps, the land cover changes have been assigned to time phases relative to the respective station opening. The CLC change interval during which the station opening occurred has been labelled as “phase 0”, and the preceding and following CLC intervals have been labelled -1 to -4 and +1 to +4, accordingly. If a station opening occurred in a year of a new CLC survey, the ending interval was defined as “phase 0”. Since there are only four CLC intervals currently available, not all phases are available for all stations. A methodological bias is caused by the fact that the first of the four CLC intervals was longer than the following intervals (10 instead of 6 years). As an example, the station of Mâcon-Loché-TGV was opened in 1981 – the first CLC interval is 1990 to 2000, hence there is no “phase 0” data for the station, and the first interval is defined as “phase 1”, up to the 2012-2018 interval as “phase 4” after the opening.

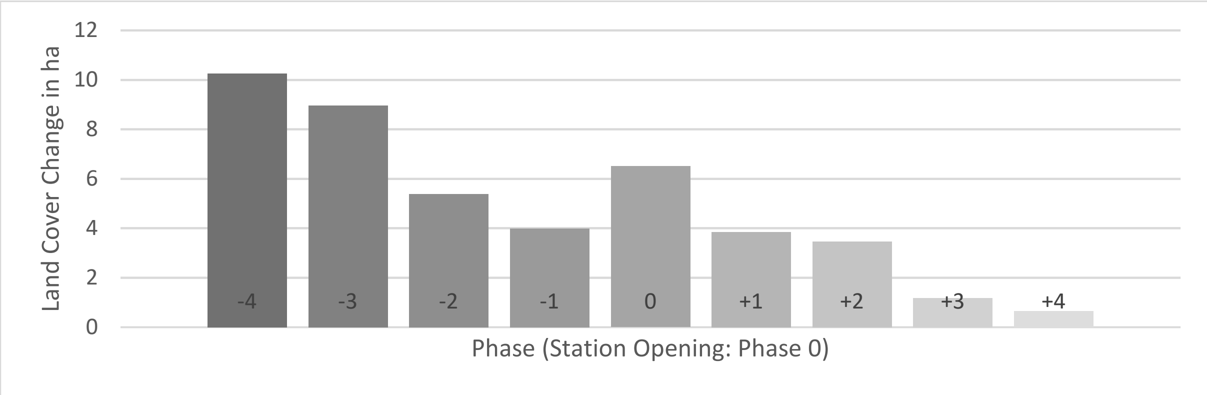
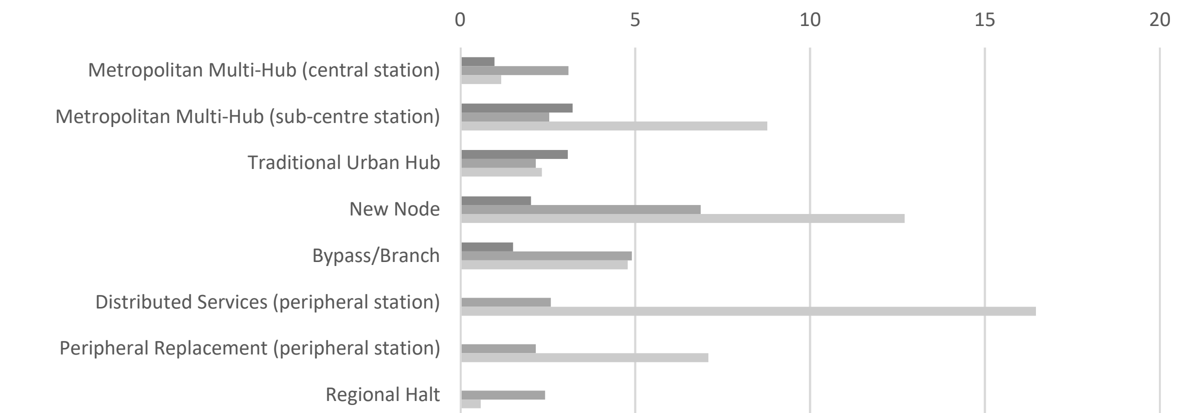


Figure 4-5*: Average size of land cover change in hectares by phase (station opening: phase 0)*

Figure 4-5 shows the average land cover change in hectares by station for the different phases, normalised by the number of stations with available data for the respective phase. An increase of land cover change around the year of the station opening (phase 0) can be seen. What is most striking, though, is the surprisingly high average land cover change in phases long before and probably entirely unrelated to the station opening. A closer investigation of the data reveals that these high values are almost entirely due to stations in Spain with a recent opening year, for which the construction boom in the country during the late 1990s and 2000s fell in phases -4 and -3. Without the Spanish stations, phase 0 exhibits the highest average land cover change. This underlines the strong influence of economic cycles on the construction activity. At the same time, it suggests that stations in Spain have been placed in areas that had seen substantial construction in the decade(s) before, indeed pointing to a reverse causality for station placement.

The diagram suggests that most development following a station opening has occurred by the end of phase 2 (at the latest, 22 years after opening for stations opened in 1990), and not many further land cover changes are to be expected thereafter. This contradicts the assumption that very long time-lags have to be accounted for in station area development.

If only stations already in service and phases -1 to +2 are considered, which can be argued to be most closely related to the station opening, most land cover changes are to “industrial or commercial units” (949 ha), followed by discontinuous urban fabric (552 ha), non-agricultural vegetated areas (480 ha), and continuous urban fabric (274 ha). Surprisingly, at 113 of the 188 stations in service until now, no land cover changes in phases -1 to +2 were recorded at all. These are often inner-city stations with an already densely built-up surrounding. The artificial, non-agricultural vegetated areas are strongly influenced by a single contributor, Stratford International station with its surrounding Olympic Park of the 2012 London Olympics (187 ha), and have therefore been excluded from the following analysis.



	Regional Halt	Peripheral Replacement (peripheral station)	Distributed Services (peripheral station)	Bypass/Branch	New Node	Traditional Urban Hub	Metropolitan Multi-Hub (sub-centre station)	Metropolitan Multi-Hub (central station)
Continuous Urban Fabric (111)	0.0	0.0	0.0	1.5	2.0	3.1	3.2	1.0
Disontinuous Urban Fabric (112)	2.4	2.2	2.6	4.9	6.9	2.2	2.5	3.1
Industrial or commercial units (121)	0.6	7.1	16.5	4.8	12.7	2.3	8.8	1.2

***Figure 4-6**: Average total increase of land cover types in hectares in phases -1 to +2 by station type*

Figure 4-6 shows the average total increase of different land cover types in hectares in phases -1 to +2 by station type. Peripheral stations ("Distributed Services" and "Peripheral Replacement") seem to be associated more strongly with industrial and commercial uses, while station locations in greater proximity to existing urban cores, such as the „New Node" (type 3) stations at urban fringes, seem to be additionally affiliated with an increase in discontinuous urban fabric, which includes residential uses. The high share of industrial and commercial uses for metropolitan sub-centre stations is noticeable, while centrally located stations seem to be relatively unconnected with land cover changes, presumably due to the already high share of continuous urban fabric. However, while the average increase per station is low, the high number of stations of the "Traditional Urban Hub" type means that the absolute land conversion around them is sizeable. The "Regional Halt" stations are not associated with significant urban development.

Surprisingly, no clear relationship between the development around a station on the one hand and the level of service and accessibility level on the other could be established, using either gravitational accessibility of population or the number of departures as indicator (see Wenner and Thierstein 2020 for details on the accessibility indicators). This might be due to the fact that accessibility levels throughout Europe are still very heterogeneous: what counts as high level of service in one country is considered unattractive in another. Instead, the results reveal that in several cases, actual accessibility levels are not matched by adequate urban density in the station surroundings, highlighting deficits and missed opportunities in terms of transit-oriented development. Also, no relationship between the architectural quality of a station and land cover change could be established, using Avery Index entries of station architects as measure (cf. Wenner 2020). However, urban stations as well as peripheral stations of the "Distributed Services" type achieved the highest average scores, while those of "Regional Halts" received the lowest.

Three groups of stations with a high absolute land cover change emerge from the analysis: First, "Metropolitan Multi-Hub (sub-centre)" stations with internationally-oriented large scale developments, such as Stratford International (London 2012 Olympic Park) and Marne la Vallée-Chessy (Euro Disneyland). Second, stations with large-scale urban redevelopment projects, sometimes deliberately coupled with HSR, such as in Cordoba, Zaragoza, Burgos, or Milano-Rogoredo. In Spain, these were often affected by the economic cycle of the construction sector. These stations are mostly of the "Metropolitan Mulit-Hub (sub-centre)" or "Traditional Urban Hub" types. The last group consists of urban fringe stations in mid-sized cities within a one-hour reach of larger metropolitan areas, such as Champagne-Ardenne TGV (Reims), Valence, Ciudad Real, and Montabaur. These regions are mostly of the "New Node" and "Distributed Services" type. The last two categories are potentially of most interest for local planners and policymakers, as there will be numerous similar spatial settings in the currently planned HSR lines.

4.6. **Discussion**

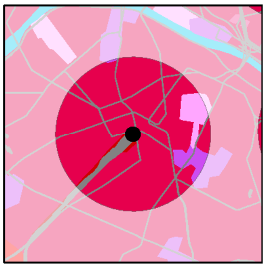
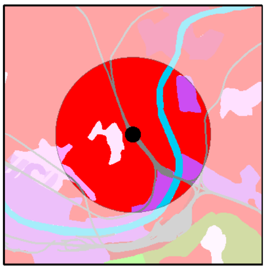
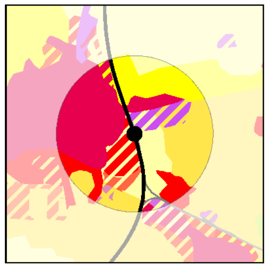
The analyses presented here were able to confirm the existing literature in several regards. First, there seems to be a slight tendency of rail infrastructure operators towards a more integrated and intermodal station policy, and a concentration of departures in one single station, for lines currently under construction (Ribalaygua and Perez-Del-Caño 2019: 597; de Meer, Ribalaygua and Elena 2012: 207). Nevertheless, a considerable share of the stations currently under construction is exurban, particularly in Spain.

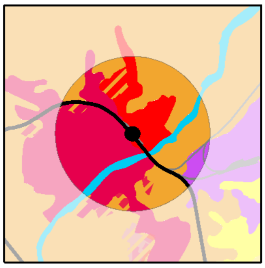
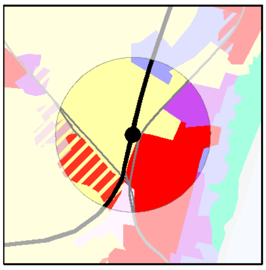
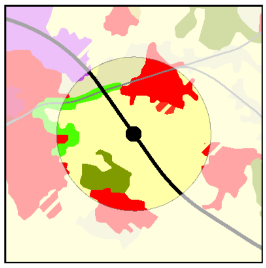
Second, the finding that peripheral stations seem to be more strongly associated with larger-scale industrial and commercial uses (Coronado, Ureña and Miralles 2019: 438; Beckerich, Benoit and Delaplace 2019: 574), while more urban locations are more attractive for residential uses, is supported by the results.

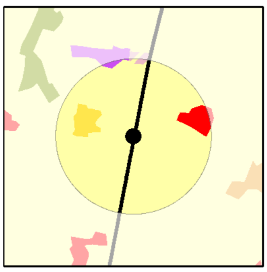
Third, neither inner-city nor completely exurban locations can be associated with strong land cover changes. This shows that a location on the urban fringes with available building land, coupled with good local public transport integration seems to be most conductive to new urban development. At the same time, the results are not very pronounced, and at more than half of all stations, no land cover changes occurred at all, pointing to the importance of other factors for urban development.

Lastly, exurban stations, far away from the next urban areas, are unlikely to attract any meaningful urban development. In his seminal work on Central Place Theory, Christaller (1933 [1968]: 106) describes a scenario in which a station similar to the "Regional Halt" effectuates a shift of urban development from an existing, declining location to the new station location. However, for current times and transport technologies, and over a relatively short period, this does not seem to be the case.

The typology presented in Table 4-1 can hence be complemented with the urban development impacts detailed in Table 4-2.

Region Type	**Metropolitan Multi-Hub**	**Traditional Urban Hub**	**New Node**
Urban Development Impact	Theoretically very high, but lack of available building space. Opportunities for sub-centres and secondary stations.	Theoretically very high, but lack of available building space.	High, attractive for residential and commercial uses.
Example	Paris Gare Montparnasse	Liège-Guillemins	Ciudad Real
CORINE Visualisation			

Region Type	**Bypass/Branch**	**Distributed Services**	**Peripheral Replacement**
Urban Development Impact	Medium, attractive for residential and commercial uses.	Peripheral station: High, attractive for commercial uses	Peripheral station: Medium, attractive for commercial uses
Example	Lleida-Pirineus	Køge Nord	Limburg Süd
CORINE Visualisation			

Region Type	**Regional Halt**
Urban Development Impact	Low
Example	TGV Haute Picardie
CORINE Visualisation	

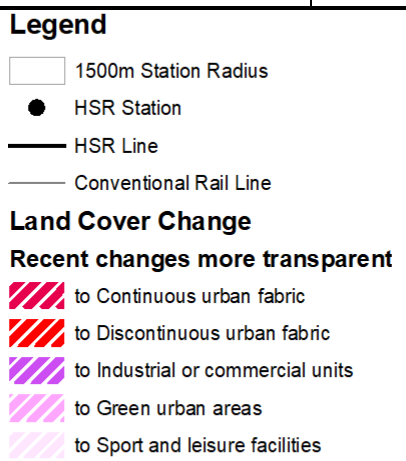


Table 4-2: *Urban Development Impacts for the regional HSR types*

4.7. **Conclusion**

This study analysed land cover changes in the surroundings of High-Speed Rail (HSR) stations in Europe. For this purpose, a database of 232 stations in 187 city-regions across eleven European countries was combined with CORINE land cover data to assess the scale and type of land cover changes. Regions served by HSR were categorised into seven types according to locational characteristics of the HSR stations. The study confirms existing literature in four aspects: (1) Station location strategies of European rail companies are changing towards more integrated, urban stations; (2) urban fringe, rather than exurban and inner-city stations, can be associated most with new urban development, as they combine locational attractiveness with available building land; (3) peripheral station locations are associated with industrial and commercial land cover changes, while more centrally-located stations are associated with general urban fabric, which includes residential uses; (4) exurban stations far from any urban areas are not associated with any substantial urban development. The data shows an increase of land cover changes during the opening phase of the infrastructure, but no change in development trend beyond the opening. Rather, it shows a decline of development activity after 12-16 years, casting doubt over the existence of long time-lags. Surprisingly, the data also shows that development around stations was strongest long before the opening, which can in most cases be traced back to the construction conjuncture in Spain before the financial crisis of 2008, highlighting the strong impact of business cycles on the construction industry. Other foreshadowing effects of new infrastructure could not be determined. Also, no relationship between the level of service at a station and the growth of urban land uses could be determined. As a result, if urban development around new HSR station is to occur, it seems to be most likely if the station is well-embedded in local and regional public transport networks and located close to existing urban agglomerations, but not surrounded by it.

The results have to been in the light of some limitations of the research design presented here, which at the same time represent further avenues for research. First, it might be the case that the development captured with this method would have occurred even in the absence of HSR, or has also occurred in other locations around the city without HSR station, due to the general local economic circumstances. The aspect could potentially be covered with the use of difference-in-differences approaches, which attempt to pinpoint effects by comparing trends of “treated” with (synthetic) “untreated” areas that are in other respects as similar as possible to the treated areas, or with instrumental variable approaches that use planned alternative station locations as comparison; however, the high number of cases exacerbates the construction of credible alternative scenarios for each case and was beyond the scope of this study.

Second, the area around the station might have represented the only available building land at the time of the inauguration of the station, and/or other factors, such as car-accessibility, have been at least equally important for urban development. In these cases, development would be merely “transit adjacent” (Peters and Novy 2012b: 13) instead of actually “transit oriented”. Development in the station surroundings can also seem generative locally, but might be redistributive in a regional perspective (Preston and Wall 2008: 406; Williger 2008: 262), particularly with respect to areas surrounding stations where rail services are reduced as a consequence of HSR introduction. Indeed, some previous studies highlight the practical importance of such constraints (e.g. Beckerich, Benoit and Delaplace 2019: 587). Besides the inclusion of more variables into the analysis and the application of more complex statistical methods, but also the application of qualitative methods, particularly interviews, represent a mitigation strategy for further future analyses.

Third, land use changes are also highly dependent on discretionary local planning decisions. Without appropriate planning, demand for construction cannot materialise, and planning must match local demand. Only with a triangulation of different methods can correlations be condensed into causalities, and can the role of local actors and strategies in facilitating or moderating development be determined. Even though local governments are often highly interested in exploiting accessibility gains for urban development, even in many cases of suitable urban fringe locations with good public transport integration, the study has shown that a lot remains to be desired in terms of transit-oriented development. An in-depth analysis of local planning documents and interviews could reveal situations where either a lack of political intent or market demand prevented development.

Finally, a densification and intensification of uses in an area surrounding a station can occur without a change of CLC classes. Particularly in the case of inner-city stations, which are often already surrounded by "continuous urban fabric", an increase in residential and commercial users and a shift in the type of firms cannot be measured using CLC data. Here, in-depth local analyses of ground floor usage and firm types must complement land cover analyses (e.g. de Meer, Ribalaygua and Elena 2012 for Spain, confirm densification effects). One way to approach this question would be the use of firm location data, which is increasingly becoming available for scientific research. At the same time, research often focuses on places with increased accessibility only. Greater attention for developments near stations whose accessibility has decreased as a result of HSR introduction, for example due to discontinuation of slower long-distance services, would merit similar comparative investigations.

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5. Eurostar Architecture: Comparing High-Speed Rail Stations in Europe

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Abstract: The spread of high-speed rail (HSR) in Europe since the 1980s has reinvigorated the role of railway stations as both spaces of public encounter and transport nodes. In reaction to the re-emerging task to design new passenger railway stations, several European railway companies have been attempting to underline this role by drawing on iconic architecture, sometimes assigning the task to star architects. This chapter explores the geographical distribution and motivations behind this strategy and presents the findings of a quantitative, comparative research across 73 railway stations in 10 European countries that have been newly built or replaced as part of HSR development. Architects' 'star status' and the public and professional recognition of their station buildings were measured using a novel approach of architecture and tourism database analysis. The chapter concludes that star architecture for HSR stations is not always utilised in proportion to the importance of a station as a transport node. It is most often applied in urban subcentres and at airport stations, less so in city centre locations. Public recognition of stations is not significantly linked to the 'stardom' of the architect, while professional recognition is. The most popular HSR stations remain refurbished, traditional inner-city stations.

Keywords: Star architecture, High-speed rail, Railway stations, Station architecture

Contributions (CRediT taxonomy): Conceptualisation, F.W.; methodology, F.W.; validation, F.W.; formal analysis, F.W.; investigation, F.W., C.A., L.A., K.D., L.F.; L.H., L.S., I.T.; data curation, F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W.; visualisation, F.W.; supervision, F.W., A.T.; project administration, F.W.

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5.1. Star Architecture for High-Speed Rail Stations

The term 'star architecture' is used to describe buildings designed by internationally renowned architects, often not only to seek a high aesthetic and functional quality but also to take advantage of the architects' prominence, for example, for marketing purposes (Ponzini and Nastasi 2016). By buying a certain 'brand', principals hope for further added value for their project, the urban surroundings or even the entire city (refer to Ponzini, Alaily-Mattar and Thierstein, Chap. 1 of this volume[9]), which however usually comes at a higher monetary cost for the building. Public buildings hosting civic institutions, such as museums or libraries, are among the most discussed cases.

This development has not stopped short of railway stations. Since the 1980s, after decades of closures and decline, the development of high-speed rail (HSR) systems has reinvigorated the role of railway stations and their surroundings as both public places and transport nodes (Bertolini 1999; Trip 2008). The need for completely new structures, often in central urban locations, in combination with the dynamism and technological progress associated with HSR has led to the involvement of internationally recognised architects in the development of HSR stations, such as Santiago Calatrava, Zaha Hadid and Norman Foster.

Rail users, like others, desire high-quality architecture, usually regardless of the prestige that comes with the architect. At the same time, railway companies in Europe are almost always public or semipublic organisations, many operating on a tight budget. This means that railway companies are faced with a trade-off and must be selective where they invest in design, often giving priority to functionality (Gerkan 1996).

This chapter, hence, addresses two questions: First, is the transport importance of a railway station higher when more star architects are involved, and vice versa? It is hypothesised that a disproportionately high 'stardom' of a station architect signals other motives than user satisfaction (such as deliberate upgrading or prestige) behind the commissioning, while a below-average status might represent a lost opportunity to advertise the rail system. Second, the chapter asks whether star architecture actually results in public and professional acclaim in the field of HSR stations. Can railway companies buy popularity by commissioning star architects?

The chapter starts with a short introduction into the history of railway station architecture and the development of HSR, followed by a short literature review on potential motivations for the use of star architecture. After developing a methodology to create a deeper understanding of the geographical distribution of star architecture for HSR, an analysis of a European HSR station database is presented and a specific quantitative approach to architecture and tourism analysis proposed. Finally, results are described and discussed.

[9] References to "this volume" refer to the edited book: Alaily-Mattar, Nadia, Davide Ponzini and Alain Thierstein (Hrsg.) (2020): About Star Architecture: Reflecting on Cities in Europe. Basel: Springer International Publishing.

5.1.1. Passenger Railway Stations as Urban Generators

Soon after the opening of the first railway lines across Europe in the 1830s, passenger railway stations had become some of the most important public buildings of their cities. They were meeting spaces and integrators of society (Alexander 2017) and attracted and generated new urban development and dynamism (Berger and Enflo 2017; Dürr 1996), and even in smaller towns, they were surrounded by an aura of cosmopolitanism, as 'gates to the world'. Large railway stations are described as secular 'cathedrals of modernity' of their time (Herzog and Leis 2010), combining innovative engineering with a representative design (van Uffelen 2010). They were the representative posts of both their host cities and the railway companies that built them. Paris' Gare du Nord and Frankfurt's Hauptbahnhof are only some of the monumental examples for this 'golden age' of rail transport in the second half of the nineteenth century. Many of these stations were built before the nationalisation of railway companies, when station architecture was one component of competition between companies.

With the spread of the private car and the expansion of air travel since the early twentieth century, rail transport suffered first a loss of demand and then of investment and prestige (Gerkan 1996). Developing new railway stations became a rare task for architects in most European countries. Railway stations lost their status as primary hubs for international travel to airports, with consequences for their image, both socially and architecturally (Schwarz 1996).

5.1.2. The Emergence of High-Speed Rail

It is rare that a declining technology experiences a revival (Banister and Hall 1993), but railway operators sought to regain market shares through the development of new services, covering larger distances at higher speeds, requiring the construction of new high-speed rail infrastructure (UIC 2018) causing such a revival. In Europe, despite progressing unification, this development initially proceeded according to the intrinsic logic of the respective national railway companies, in several countries at the same time. Following the example of the Japanese 'Shinkansen' (Tokyo-Osaka, starting in 1964), HSR lines were opened by Italy's Trenitalia (1977, Rome-Florence), France's SNCF (1981, Lyon-Paris) and Germany's Deutsche Bahn (1991, Hannover-Würzburg). RENFE in Spain followed in 1992 with the route Madrid-Seville, and since the completion of the channel tunnel in 1994, London is served by Eurostar. Strong passenger growth indicated the success of this strategy. Over time an international European network has developed, covering also Austria, Belgium, the Netherlands and Sweden, also due to the Trans-European Networks (TEN) initiative of the European Union. On a global scale, China's main railway operator has fast expanded its network in the twenty-first century, which is now the largest in the world. A number of further new HSR lines are currently under construction or in planning. However, due to the comparable socio-political conditions that set the framework in which star architecture is implemented, especially the role of local government, public participation and market forces, and according to the scope of this book, this chapter concentrates on Europe.

HSR is mainly defined as "specially built high-speed lines equipped for speeds generally equal to or greater than 250 km/h" (European Council 1996). Despite this common definition, the actual implementation of HSR varies. Particularly, there are notable differences in the station placement policies of the different railway companies, which have consequences for the number and type of stations that are (re)built for HSR. Some concentrate on providing direct access to existing stations in city centres via connecting conventional lines (Germany, Italy), while others have at least in the past followed a strategy of 'out-of-town' stations particularly for medium-sized and small cities (France, Spain), prioritising speed over local embeddedness. The choice of policy is influenced by settlement patterns, the political system and the quality of the existing rail infrastructure, inter alia. Railway companies in unitary countries with a single, dominating metropolitan centre tend to develop a more hierarchical HSR system focussed on the main city, while a more piecemeal approach with a stronger emphasis on incorporating the existing infrastructure can be seen in other countries. Meanwhile, most railway companies have also partially shifted their attitude towards air travel from competition to co-operation at least for long distances (Terpstra and Lijesen 2015), with the effect of a deliberate inclusion of airports in the HSR networks.

The European railway companies use different approaches for station design decisions as well: most use design competitions, but direct commissioning also occurs. The SNCF uses its own in-house architecture consultancy, AREP, which is responsible for a majority of the HSR station designs. It meanwhile exports its services to other firms and countries.

Finally, a number of European rail companies have actively opted not to develop new high-speed networks. Some of them have emphasised the improvement of their services through targeted upgrades of conventional lines in combination with a better coordination of timetables and third-party services (particularly Switzerland and the Netherlands). Even though there are many publicly acclaimed rail station redevelopments in these cases as well, for better comparability only HSR stations are analysed for this chapter.

It is important to note that the emergence of HSR has occurred simultaneously to the partial transformation of many railway companies in Europe from public authorities into semi-private forms of organisation or even full privatisation. These reforms often gave railway companies a greater autonomy and responsibility over their finances and reduced public service obligations. As a result, many (re)discovered the economic value of their centrally located real estate, fuelling a stronger commercialisation of railway stations (Hoffmann-Axthelm 1996) but also incentivising a more active role of railway companies in urban development.

5.1.3. Research Perspectives on High-Speed Rail Stations for Urbanism and Architecture

In spatial research, HSR has attracted some attention due to its (presumed) ability to direct urban development by virtue of its accessibility effects. Accessibility, understood as the potential of opportunity for interaction (Hansen 1959:75), is among the main drivers behind location choices of households and firms, especially since knowledge-intensive work is becoming more important (Thierstein et al. 2016; Zhao, Bentlage and Thierstein 2017). On the one hand, it is assumed that HSR is able to revitalise and rebalance spatial economic structure (Ahlfeldt and Feddersen 2018) and that a reconcentration on public transport will help to (re)generate lively, sustainable, urban districts with the stations as both central transport node and as a place of encounter and urban development (Bertolini and Spit 1998; Trip 2008). On the other hand, there is also the expectation that it will lead to further economic polarisation and hierarchisation (Chen and Hall 2015; Garmendia, Ribalaygua and Ureña 2012; Vickerman 1997) and urban sprawl (Schütz 1997). Relatively little attention has been paid in international research to the station buildings and the urban design of their immediate surroundings as part of these transformation processes (Ponzini 2013) – among the few exceptions (refer to Morka 2012).

This is despite the fact that several of the newly built HSR stations, some of which are designed by internationally renowned architects, have attracted considerable international public and professional attention (e.g. Jencks 1995). The stations of Lyon-Saint Exupéry (1994, formerly Satolas) and Liège-Guillemins (2009), designed by Santiago Calatrava (Figure 5-1), and, more recently, Napoli Afragola (2017) by Zaha Hadid are examples.

Figure 5-1*: The new Liège-Guillemins station by Santiago Calatrava. Opened in 2009, it is one example of several newly built high-speed rail stations designed by internationally renowned architects. (Source: Photograph by author)*

5.1.4. Star Architecture as Engine of Upgrading?

Star architecture is usually associated with principals who try to increase the prestige and economic value of their real estate through a design that is unique and branded. Increasingly also cities participate in this competition for professional and public attention by commissioning internationally renowned architects for public buildings, with the hope of attracting tourists, companies and employees in the longer term (the 'Bilbao effect', Plaza, Tironi and Haarich 2009; Alaily-Mattar, Dreher and Thierstein 2018). Consequentially, usually locally bound actors push for star architecture projects (refer to the Introduction of this volume[9]).

Railway companies on the other hand are mostly state-owned national quasi-monopolists with little competition at least for short- and medium-range distances. As a result, the design of their stations theoretically has little impact on demand, as users will have to use them anyways. The predominant perspective of rail companies is that of balanced, hierarchical networks. The station site, for example, cannot usually be strategically chosen according to the requirements of star architecture. Often companies aim for a recognisable, similar design across all stations. At the same time, many of the rail companies are operating on a tight (public) budget. On this background it is a little surprising that star architects have been tasked with the design of HSR stations as well. When the international union of railways postulates that 'stations are becoming legitimately more spectacular' (UIC 2018), it suggests that railway companies have a self-interest in providing such architecture for their customers.

However, literature points to a potential alliance between railway companies and local actors. Gerkan (1996, author's translation) sees architecture – taken as 'the appreciation of its contents' – as one way to accomplish a social 'gentrification' of the railway station and its surroundings, that should be in the interest of railway companies:

> *As long as railway stations are centres of red-light districts, focal points of the drug scene and meeting places of social outsiders, these phenomena will represent a high psychological barrier towards rail transport […]. If the aim is pursued to regain public appreciation for rail transport, it is imperative to fundamentally change the milieu of railway stations […].*

This allies with railway companies and inner-city landowners, often influential in local political decisions. In addition, prestige can incentivise local and national governments. In the inauguration speech of Napoli Afragola station, the prime minister of Italy, Paolo Gentiloni addresses this point: "to those who say that this work is too great, Pharaonic, I reply that Pharaonic means leaving the mark of great civilisations and Italy must have the pride of leaving these legacies" (Del Porto and Lucarelli 2017, author's translation).

Star architecture for railway stations can hence be conceived of as a strategic tool to achieve not only architectural qualities for rail users but also to initiate social upgrading of both the station and its surroundings. In-depth case studies by students as preparation for this research suggest that local actors are indeed able to highjack HSR development projects and push for their own agenda, while the national actors have less interest in star architecture in the first place.

5.2. A Database of European HSR Stations and Their Architects

Since a consistent framework for the analysis of star architecture is still missing, particularly pertaining to quantitative approaches, it is first necessary to establish a definition of star architecture, which is not meant to claim universal validity but to structure the subject for the purpose of this chapter. Despite the categorisation presented in the introduction of this book that the term 'star' in 'star architecture' can relate to both the status of the building and the architect, a more limited definition following Alaily-Mattar, Dreher and Thierstein (2018) is applied here, that 'star architecture' always involves an internationally renowned architect.

Another difficulty is actually the way 'architecture' is defined. While the multiple dimensions of architects' work are acknowledged, this chapter concentrates on the (outside) appearance of buildings as the design component that can be most directly witnessed by the public and reproduced by the media.

This chapter starts from the baseline hypothesis that the commissioning of a star architect is related to the importance of a station as a transport hub. We borrow the concept of the 'node-place model' by Bertolini (1999) here, who developed a similar methodology to describe a corridor of optimum combinations of accessibility and urban and functional density. An above-average status of the architect of a station compared to its transport importance signals other motives than passenger satisfaction, particularly a local desire for upgrading, behind the commissioning of stars, while a below-average status might represent a lost opportunity to advertise the rail system.

This chapter is particularly interested in the geographical distribution of above-average use of star architecture. While it is assumed that above-average use of star architecture can be found in all countries studied, that is the dependence more on local factors than on the influence of the (national) railway companies, we expect to see outliers which lend themselves as candidates for potential in-depth studies. Their spatial pattern in turn enables further hypothesis formation. Given the competition for attention with other buildings, particularly cultural ones (refer to Chap. 4 by Thierstein, Alaily-Mattar and Dreher in this volume[9] for an impact model), it can furthermore be assumed that in an intracity perspective, star architects are more often commissioned for stations in inner-city contexts.

This chapter also tests whether the involvement of a star architect leads to an above-average public and professional recognition of that station. The assumption is that additional investment in a station building in the form of the commissioning of a star architect will ultimately lead to a higher recognition of this station among the general public as well as architecture professionals. The assumption is also that star architecture stations achieve a higher recognition than the existing, traditional stations.

5.2.1. A Method to Quantify the 'Stardom' of Architects

To test the hypotheses, a quantitative database was compiled of all stations that have been directly connected to newly built HSR lines in Europe between 1981 and 2018. This resulted in a list of 167 stations in ten European countries. Of these 167 stations, 50 (30%) are entirely new stations at a location where no railway station had existed before. In another 23 cases (14%), the previous station buildings were completely replaced by a new one. The remaining are renovated (29, 17%), extensions (6, 4%) and no changes (59, 35%). The further analysis concentrates on the 73 cases where entirely new station buildings were built, either because of a new location or a replacement (see Appendix). For these stations, data was gathered on the commissioned architects, urban integration and context, as well as traffic statistics, inter alia. While for 16 stations no architect could be identified from literature, there were also 5 cases of stations with no specific involvement of architects. Usually these were built using a modular system, consisting of barely more than platforms and a small shelter. These stations were excluded from further analysis.

As mentioned, quantitative analyses of star architectural projects are still rare (Ponzini and Manfredini 2017). This is partly due to the difficulty in measuring abstract concepts like 'star' characteristics of an architect or the recognition of a building directly. Hence a novel methodology of using online databases and user-generated data to approximate these variables was applied. The number of search results for an architect on the Avery Index,[10] a comprehensive architecture periodicals database, was used as a proxy for the 'star' status of an architect. In case of multiple architects involved, the highest score of any of the parties was used. For comparison, other indices such as *Google* search results as proxy for general public recognition of 'star' status were tested but revealed less nuanced results.

With regard to the professional recognition of single station buildings, the *Avery* Index entries were used as well, this time for the building. We used the average number of search results for both the English and local name of the station building. Public recognition of buildings was measured through scores on the travel review website *TripAdvisor*.[11] On this website, users can review tourist sights, inter alia. For each station record was made of whether the station is listed as a sight (in the category 'things to do'), how many users reviewed it, the average rating of all reviewers (measured in 0.5 intervals between 0 and 5, 5 being best) and the rank of this rating compared with all other tourist sites in the respective city. *TripAdvisor* self-advertises as 'the world's largest travel site' and 'home to the world's largest travel community of 490 million average monthly unique visitors' (*TripAdvisor* 2018). Even though the website owners actively manage the reviews, the high number of reviews per sight leads us to assume that the source is sufficiently unbiased and suitable as a source, especially in relative terms. All data was gathered in September 2018.

[10] https://library.columbia.edu/locations/avery/avery-index.htm
[11] https://www.tripadvisor.com

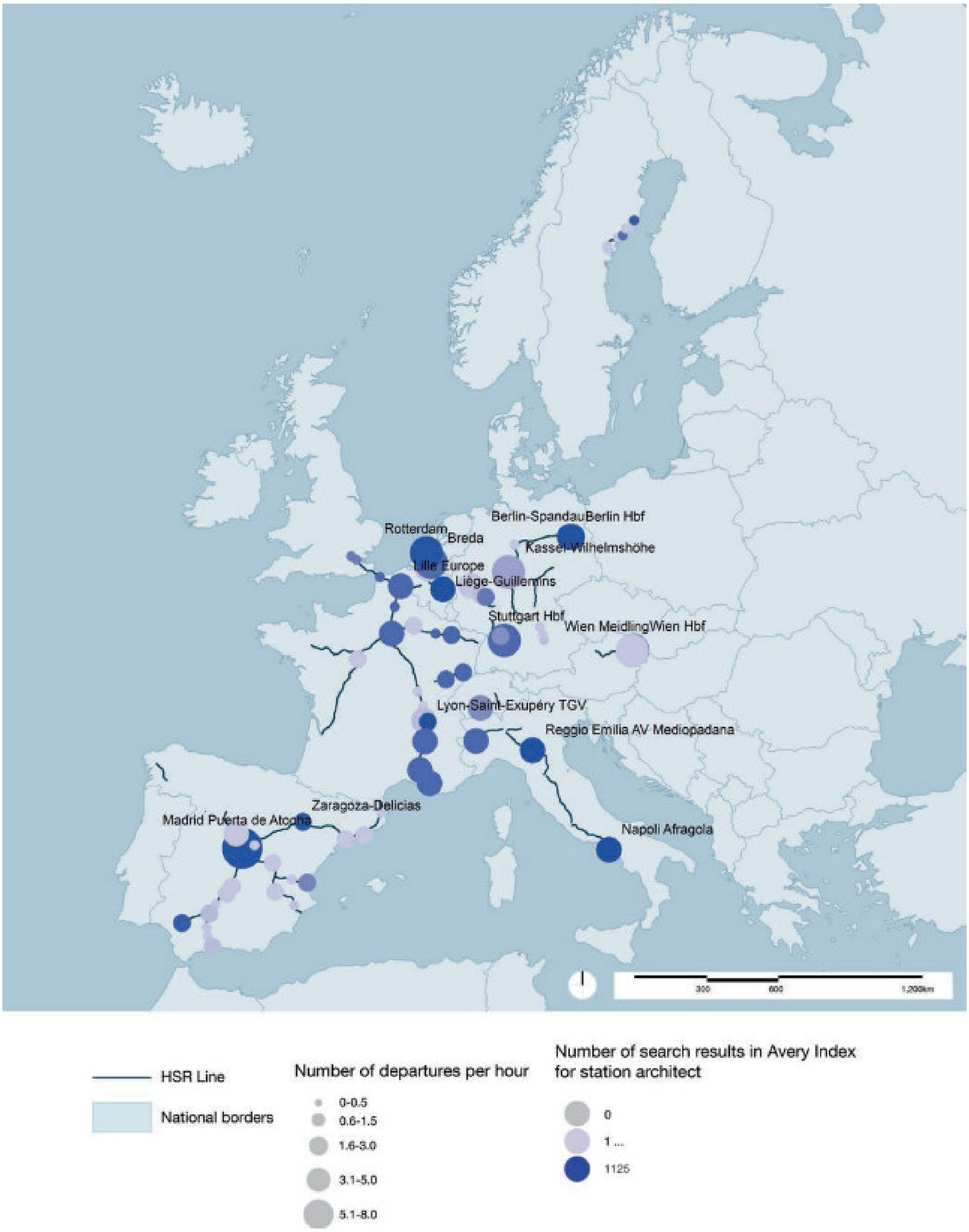

Figure 5-2: *Search results on Avery Index for station architect and number of departures for HSR stations in Europe. While 'stardom' of the station architect corresponds with its transport importance in most cases, there are notable exceptions, such as Vienna Main Station (Wien Hbf) and Kassel-Wilhelmshöhe with a lower Avery score of the station architect than expected and Lyon-Saint Exupéry with a higher score*

Country	Average search results on *Avery* Index
Austria	20
Belgium	638
France	123
Germany	136
Italy	624
Netherlands	222
Spain	177
Sweden	56
Switzerland	14
United Kingdom	26
All	164

***Table 5-1**: Average Avery scores for station architects of analysed HSR stations by country. It shows that Belgium and Italy score highest, while both Germany and Austria have the most serviced stations they are seldom made use of star architects. Source: By Author*

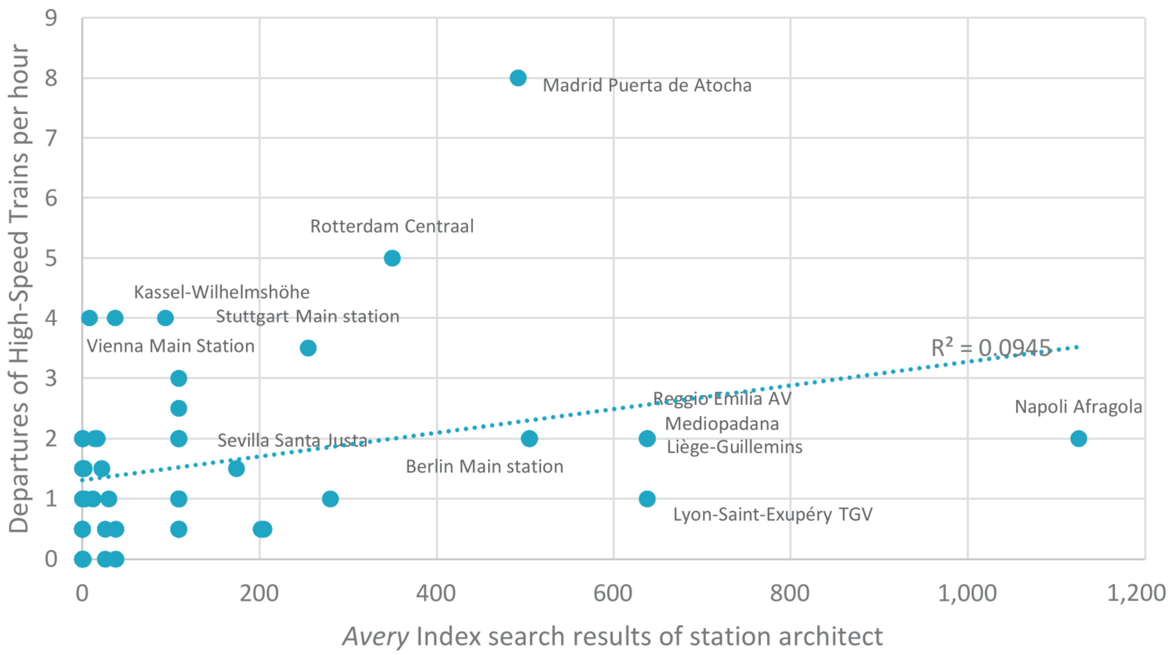

***Figure 5-3**: Relationship between a station's importance as transport node, measured in departures per hour, and 'star' status of a stations architect (Avery Index score). It demonstrates a relationship between the more important stations that made use of famous architects, with Berlin main station and Sevilla Santa Justa close to the 'balanced' line. (Source: Author)*

5.3. Results: Eurostar Architectures

Figure 5-2 shows a map of the stations analysed for this chapter. The size of the dots symbolises the importance of a station as transport hub, measured by the number of high-speed train departures per hour; the colour indicates the 'star' status of the stations' architect, measured in the number of *Avery* Index search results. The *Avery* results range from 0 to 1125 (Napoli Afragola, Zaha Hadid). A score of 200 or more is rare, and only achieved by well-known international architects, even though this chapter does not set a certain threshold for 'stardom', instead taking a gradual perspective. It becomes clear that there are several stations with a relatively low number of departures, but high 'star' status, and vice versa.

Urban location and context	Average search results on Avery Index	TripAdvisor reviews	Average rating	Average number of reviews	Average rank of sight within city
Inner city	132	8	3,9	1632	61,68%
Urban sub-centre	243	5	3,8	448	71,86%
Greenfield, but close to city	142	3	3,2	252	48,74%
Peripheral	32	0			
Airport	422	0			
All	164				

Table 5-2: *Average Avery and TripAdvisor scores for stations based on their urban location and context. It demonstrates that star architecture is found in urban sub-centre locations and at airports, and less often at inner city stations. Source: By Author*

A look at the average Avery search results for station architects of these 73 stations for the different countries (refer to Table 5-1) reveals that particularly in Belgium and Italy, HSR stations are built by star architects. On the other hand, Austria and Germany show some of the most serviced stations that at the same time have low Avery results for their architects. Avery results were available for 53 of the 73 stations.

Figure 5-3 shows the relation between a station's importance as transport node, measured in departures of high-speed trains per hour, and the 'star' status of its architect, measured in Avery Index search results. It shows that the relationship between the importance of the station and the fame of the architect is very low, with a coefficient of determination R2 of 0.09.The linear trend line can be read as a 'balanced' combination. For example, the stations Berlin Hauptbahnhof (main station) and Sevilla Santa Justa are close to this line – here, the 'stardom' of the architect was in line with the importance of the station. Lyon-Saint Exupéry TGV, on the other hand, only has one high-speed train departure per hour on average – a low figure if contrasted with the Avery Index score of 638 for the architect Santiago Calatrava, indicating an 'excess' of star architecture for this situation. Vice versa, Rafael Moneo, the architect of Madrid Puerta de Atocha station with its eight departures per hour, has a comparatively low score of 492.

Table 5-2 shows the average 'stardom' of station architects for different urban locations and contexts. Other than expected, both peripheral and inner-city stations have below-average scores. Instead, star architecture can especially be found in urban sub-centre locations and at airport stations. The TripAdvisor reviews show a general preference for stations in urban contexts, with the urban sub-centre stations serving more as landmarks than the inner-city stations – possibly due to the fact that inner-city stations fade in comparison to other nearby buildings.

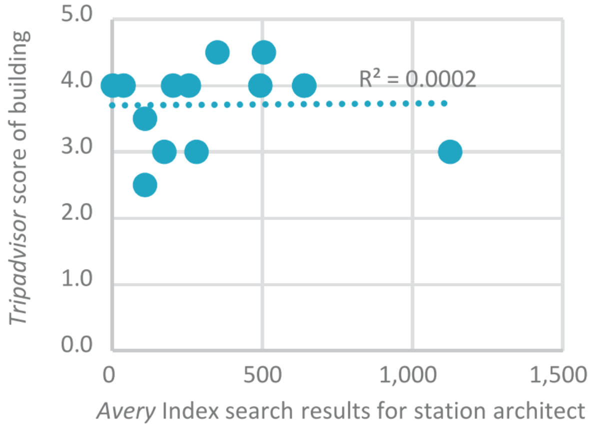

Figure 5-4: *Relationship between public recognition (TripAdvisor Score) and 'star' status of a station's architect (Avery Index search results for station architect). It demonstrates as negligible and that and public recognition of stations can be achieved without star architects. (Source: By Author)*

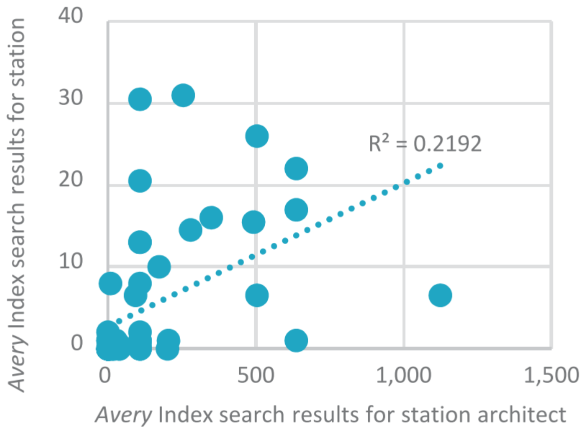

Figure 5-5: *Relationship between professional recognition (Avery Index search results for station) and 'star' status of a stations architect (Avery Index search results for station architect). It is suggested, through this graph, that professional acclaim is much more linked to 'star' status that public recognition. (Source: By Author)*

Figure 5-4 shows the relationship between the public recognition of a station's architecture (TripAdvisor Score) and the star status of its architect (number of Avery Index search results). The R^2 is almost 0, indicating no relationship between the variables. Only 15 of the 73 analysed stations have a rating on TripAdvisor, rendering the sample very small – these are however the largest and most important ones. The remaining stations almost all score low on the Avery Index. The lowest Avery score (37) despite a relatively high TripAdvisor ranking (4.0) is Vienna Main Station, showing that public recognition can be achieved without star architects. Vice versa, Napoli Afragola, designed by Zaha Hadid and opened in 2017, has a very high architect Avery score (1125) but a low TripAdvisor ranking (3.0). The station is still very new and not yet well connected to local public transport, which could have led some users giving it a lower score irrespective of the actual question of its quality as a 'sight'. Without this outlier, there is a slightly positive relationship between both variables, indicating a small but positive effect of star status on public recognition. Figure 5-5 on the other hand shows a stronger relation between the Avery Index search results for a station, that is, its professional recognition, and the results for its architect (R2 = 0.21). It suggests that professional acclaim is much more linked to 'star' status than public recognition.

The last assumption regards whether star architecture stations achieve higher public recognition than refurbished traditional stations. This must be denied: both the top stations with the highest rank within their city and the stations with the highest rating in Europe are mostly traditional; inner-city stations, Amsterdam Centraal and Antwerpen Centraal, are among the top ten sights of their respective cities, while Berlin and Leipzig main stations also achieved high ranks. Amsterdam Centraal is also the most reviewed HSR railway station with 14,457 reviews. Together with London St. Pancras International, these stations also enjoy the highest rating of 4.5. The highest ranking star architecture stations are Rotterdam Centraal by Benthem Crouwel architects, Meyer and Van Schooten architects and West 8 (rank 3 of 162 in Rotterdam) and Reggio Emilia AV Mediopadana by Santiago Calatrava (rank 10 of 82 in Reggio Emilia). At the same time, other star architecture stations receive only mixed reviews, such as Jean Nouvel's redesign of Bruxelles Midi (3.5) or Zaha Hadid's Napoli Afragola (3.0). This suggests that star architecture stations can play in the highest league of public acclaim if they are well designed, but star status is by far not a guarantee for recognition. Rather, the high ratings for refurbished stations show that traditional, inner-city stations are still the most popular.

5.4. Conclusions: The Space of Eurostar Architectures

The results have shown that star architecture is utilised to a varying degree by the different European railway companies. On the one hand, the utilisation of star architecture for HSR stations is in some cases proportional to the importance of the respective station as transport node, which indicates an appropriate use of the strategy. On the other hand, there are several significant exceptions. These exceptions hint at situations where other motivations than the rail users, particularly local urban upgrading or prestige, were driving forces. If railway stations are to remain inclusive, democratic spaces, these upgrading effects must be observed with care. The finding that redeveloped historical station buildings attract a higher recognition than most star architecture buildings furthermore shows the potential for working with the existing structures. Further research can investigate the function of such stations at the urban and regional scales.

All airport stations in this dataset were designed by star architects, by the measure of their Avery Index score. It is unclear, however, if this must be attributed to the competition effect of direct neighbourhood or the influence of airport operators themselves, who assign their own architects for the airport stations also, as in the case of Cologne/Bonn Airport station (designed by Murphy/Jahn Architects). So, it might simply be another example that so far 'airport architecture is qualitatively highly superior to railway station architecture' (Hempel 1996, author's translation), as one critic put it.

Methodologically, the attempt to quantify 'star' status and recognition of buildings using Internet sources has proven to be difficult. Pitfalls in the form of missing data, unclear intentions of user-generated data and questions of manipulability limit the validity and make it difficult to attribute effects clearly. TripAdvisor, like many similar web portals with user-generated content, is a managed platform; its source code is not published, turning the exact calculation algorithms for scores into a 'black box', despite their plausibility at first glance. Even though it is the largest website of its type, by far not all stations have reviews, leading to small sample sizes, and wherever they exist, it cannot be excluded that visitors were voting on the transport quality of the station, rather than the design quality, even though there is a separate category for this on the website. The Avery Index, maintained by the Columbia University, on the other hand, might favour Anglophone publication and hence represent a biased view of architectural recognition.

Nevertheless, there are further potentials for quantitative approaches even for questions that rely heavily on personal judgement. Particularly travel websites such as TripAdvisor still present a huge untapped reservoir for science (refer to Chap. 9 by Chareyron and Jacquot in this volume[9]), for example, with other types of civic institutions, such as museums, which would likely yield more robust results, as these usually attract more reviews. It would be interesting as well to compare such evaluations over a longer time span, to see if public recognition for star architecture is fading over time or whether it can exert a lasting influence.

5.5. **Appendix**

List of stations that have been newly built or completely replaced in the course of HSR introduction.

Name	**Year of opening**	**Country**	**Municipality**	**Architect**
Aix-en-Provence TGV	2001	France	Aix-en-Provence	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Albacete-Los Llanos	2010	Spain	Albacete	Unknown
Allersberg (Rothsee)	2006	Germany	Allersberg	Not applicable
Antequera Santa Ana	2007	Spain	Santa Ana	L35 Arquitectos
Antwerpen-Luchtbal	2009	Belgium	Antwerpen	Not applicable
Avignon TGV	2001	France	Avignon	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Gare de Belfort-Montbéliard TGV	2011	France	Belfort	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Berlin Hauptbahnhof	2006	Germany	Berlin	Gerkan, Marg und Partner
Berlin-Spandau	1998	Germany	Berlin	Gerkan, Marg und Partner
Besançon Franche-Comté TGV	2011	France	Besançon	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Breda	2009	The Netherlands	Breda	Koen van Velsen Architects

Name	Year of opening	Country	Municipality	Architect
Gare de Calais-Fréthun	1993	France	Fréthun	Jean-Marie Duthilleul & Etienne Tricaud/ AREP
Camp de Tarragona	2006	Spain	La Secuita	Unknown
Champagne-Ardenne TGV	2007	France	Reims	Pierre-Michel Desgrange
Ciudad Real	1992	Spain	Ciudad Real	Unknown
Córdoba	1992	Spain	Córdoba	Gabriel Rebollo, José Miguel Asensio, Ángel Rebollo y Jorge Benítez
Cuenca-Fernando Zóbel	2010	Spain	Cuenca	ADIF (Infrastructure Operator Spain)
Ebbsfleet International	2007	United Kingdom	Gravesend	Alastair Lansley and Mark Fisher
Figueres-Vilafant	2010	Spain	Figueres	Unknown
Girona	2013	Spain	Girona	Unknown
Guadalajara-Yebes	2003	Spain	Yebes	Unknown
Hannover Messe/Laatzen	1991	Germany	Laatzen	Unknown
Hörnefors	2010	Sweden	Hörnefors	Arkinova Architects KB
Husum(S)	2010	Sweden	Husum	Sweco (PeGeHillinge, Margareta Diedrichs)
Ingolstadt Nord	2006	Germany	Ingolstadt	Maier Neuberger Architekten GmbH
Kassel-Wilhelmshöhe	1991	Germany	Kassel	Andreas Brandt, Giovanni Signorini, Yadegar Asisi (Entwurf), Peter Schuck (Umsetzung)
Kinding (Altmühltal)	2006	Germany	Kinding im Altmühltal	Not applicable
Köln/Bonn Flughafen	2002	Germany	Köln	Murphy/Jahn Architects
Kramfors	2010	Sweden	Kramfors	Unknown
Le Creusot Montceau Montchanin TGV	1981	France	Montchanin	Unknown
Liège-Guillemins	2002	Belgium	Liège	Santiago Calatrava
Lille Europe	1993	France	Lille	Jean-Marie Duthilleul & Etienne Tricaud/ AREP
Limburg Süd	2002	Germany	Limburg	Schuster Architekten
Lorraine TGV	2007	France	Louvigny	Jean-Marie Duthilleul & Etienne Tricaud/ AREP
Gare de Lyon Part-Dieu	1981	France	Lyon	Eugène Gachon and Jean-Louis Girodet
Lyon Saint-Exupéry TGV	1994	France	Colombier-Saugnieu	Santiago Calatrava
Mâcon Loché TGV	1981	France	Mâcon	Unknown
Madrid Puerta de Atocha	1992	Spain	Madrid	Jose Rafael Moneo

Name	Year of opening	Country	Municipality	Architect
Málaga María Zambrano	2007	Spain	Málaga	COT & Partners
Marne la Vallée-Chessy	1994	France	Marne la Vallée	Jean-Marie Duthilleul & Etienne Tricaud/ AREP
Medina del Campo AV	2015	Spain	Medina del Campo	Unknown
Meuse TGV	2007	France	Les Trois-Domaines	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Montabaur	2002	Germany	Montabaur	Jux and Partner
Napoli Afragola	2017	Italy	Afragola	Zaha Hadid
Noorderkempen	2009	Belgium	Brecht	Not applicable
Nordmaling	2010	Sweden	Nordmaling	Arkinova Architects KB
Örnsköldsvik C	2010	Sweden	Örnsköldsvik	Sweco (PeGe Hillinge, Pekka Leppänen, Margareta Diedrichs)
Örnsköldsvik Norra	2010	Sweden	Örnsköldsvik	Unknown
Puente Genil-Herrera	2007	Spain	Herrera	OPTA arquitectos
Puertollano	1992	Spain	Puertollano	Unknown
Reggio Emilia AV Mediopadana	2013	Italy	Reggio nell'Emilia	Santiago Calatrava
Requena-Utiel	2010	Spain	Requena	ADIF (Infrastructure Operator Spain)
Rotterdam Centraal	2009	Netherlands	Rotterdam	Team CS (Benthem Crouwel architects, Meyer & Van Schooten architects and West 8)
Segovia-Guiomar	2007	Spain	Segovia	OPTA arquitectos
Sevilla Santa Justa	1992	Spain	Sevilla	Cruz y Ortiz
Siegburg/Bonn	2002	Germany	Siegburg	Hartmut de Corné
Stratford International	2007	United Kingdom	London	Alastair Lansley and Mark Fisher
Stuttgart Hauptbahnhof	1991	Germany	Stuttgart	Christoph Ingenhoven
TGV Haute-Picardie	1993	France	Ablaincourt-Pressoir	Jean-Marie Duthilleul & Etienne Tricaud/ AREP
Torino Porta Susa	2009	Italy	Torino	AREP with Jean-Marie Duthilleul, Etienne Tricaud, Silvio d'Ascia and Agostino Magnaghi
Tullnerfeld	2012	Austria	Tulln	Günter Lautner
UmeåÖstra	2010	Sweden	Umeå	White Arkitekter
Vaihingen (Enz)	1991	Germany	Vaihingen	Schmitt, Kasimir & Partner
Valence TGV	2001	France	Alixan	Jean-Marie Duthilleul & Etienne Tricaud/AREP
Valencia Joaquín Sorolla	2010	Spain	Valencia	IDOM

Name	Year of opening	Country	Municipality	Architect
Västeraspby	2010	Sweden	Apsby	Not applicable
Vendôme-Villiers-sur-Loir	1989	France	Vendôme	Unknown
Villanueva de Cordoba-Los Pedroches	2014	Spain	Villanueva de Cordoba	Unknown
Villena AVE	2013	Spain	Villena	ADIF (Infrastructure Operator Spain)
Visp	2007	Switzerland	Visp	Steinmann & Schmid
Wien Hauptbahnhof	2012	Austria	Vienna	Atelier Albert Wimmer (Wien), Atelier Ernst Hoffmann (Wien) and Theo Hotz Architekten und Planer (Zürich)
Wien Meidling	2012	Austria	Vienna	Unknown
Zaragoza-Delicias	2003	Spain	Zaragoza	Carlos Ferrater, José María Valeround Félix Arranz

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6. Regional Urbanisation through Accessibility? – The “Zweite Stammstrecke” Express Rail Project in Munich

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Abstract: Transport accessibility is one of the most significant locational factors for both households and firms, and thus a potentially self-reinforcing driver of urban development. The spatial structure and dynamics of accessibility hence have the potential to alter the locational choices of households and firms significantly, leading to concentration and de-concentration processes. In spite of recent innovations in automotive technologies, public transport systems remain crucial for the functioning of metropolises. In this paper, we use the case of public transport in the Munich Metropolitan Region (MMR) in Germany to (1) discuss whether public transport in the past has contributed to regional urbanisation, the blurring of urban and suburban spaces; (2) model future accessibility changes due to the ongoing mega-infrastructure project “second trunk line” (“Zweite Stammstrecke”) for suburban trains and their likely effects on processes of regional development; (3) compare the balance of accessibility and functional density at stations in the MMR and (4) recommend a planning strategy based on an integrated urban and transport planning philosophy. We argue that particularly the monocentric design of the project means that it will intensify and extend the scope of suburbanisation and metropolisation, while planning should aim for a greater regionalisation of economic activity.

Keywords: public transport; accessibility; railway stations; integrated urban and transport planning; commuting; metropolisation; suburbanisation; planning strategies

Contributions (CRediT taxonomy): Conceptualisation, F.W.; methodology, F.W.; validation, F.W., A.T.; formal analysis, F.W., K.A.D., M.H., A.P., M.S., J.W.; investigation, F.W., K.A.D., M.H., A.P., M.S., J. W.; data curation, F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W., K.A.D., M.H., A.P., M.S., J.W., A.T.; visualisation, F.W., K.A.D., M.H., A.P., M.S., J.W.; supervision, F.W., A.T.; project administration, F.W.

6.1. Introduction

It is often argued that spatial dynamics in developed countries during the last decades are characterised by new complexities. The seemingly clear-cut and hierarchical inner-regional relationship between urban cores as employment centres and expanding residential suburban areas is increasingly blurring and being supplemented by a new simultaneity of tendencies of employment de-concentration and re-urbanisation of households. “Regional urbanization” (Soja 2015) or “Zwischenstadt” (Sieverts 1997) are some of the labels given to these dynamics. This new parallelism of concentration and de-concentration can be attributed to a range of factors, among them changes in the economic system such as the rise of the knowledge economy (OECD 1996), as well as demographic developments (Simons and Weiden 2016).

New transport technologies and infrastructure are other important drivers of changes in regional settlement structures. For households, transport infrastructure provides accessibility to jobs, services, leisure and retail facilities, while for firms it provides access to (potential) employees, customers and business partners, and hence constitutes an important locational factor. Transport networks can be structured in a monocentric or polycentric way, which influences the regional distribution of accessibility and subsequently settlement dynamics. In this paper, we discuss the relationship of patterns concentration and de-concentration of households and employment with transport infrastructure improvements, particularly public transport infrastructure, in an inner-regional perspective, using the case study of the currently planned major passenger rail project “Second Trunk Line” (“Zweite Stammstrecke”) in the Munich Metropolitan Region (MMR). There has been no analysis of this project with regard to these dynamics in academic literature yet.

First, we briefly discuss the theoretical background of four dynamics—de-concentration and concentration of households and employment—separately and in their relation to transport infrastructure improvements. We then introduce our case study area and project, including previous studies on land use-transport relationships in the region, which mostly conclude that the MMR continues to be a prime example of suburbanisation and metropolisation. We pose four research questions in this paper, which are also reflected in the methods and results sections. (1) First, we ask whether more recent data shows signs of changes for the MMR that point more into the direction of re-urbanisation and regionalisation of economic activity than identified by previous literature. We hypothesize that this is the case, as most of the previous studies on the topic for the MMR have been published a while ago, and they predate the transition to the knowledge economy. Based on the results, we (2) ask which dynamics and patterns of accessibility the “Second Trunk Line” project produces, and which consequences for demand by different users of space are likely to result, using a gravitational accessibility modelling method. Our hypothesis is that accessibility gains will accrue mainly to those locations that already are highly accessible, due to the monocentric alignment of the planned new rail line. We then take a more normative approach that seeks to balance accessibility and functional density and (3) ask whether the current spatial structure still matches the new accessibility opportunities levels in the region. (4) Lastly, we ask what regional planning should do in response to these changing demands, based on recent integrated urban and transport planning philosophies and draw conclusions for metropolitan regions in general. By doing so, we contribute to the growing discussion in academic literature on sustainable urban structures.

We conclude that despite slight tendencies for a dispersion of economic activity and a polycentric development in the immediate surroundings of the city of Munich, the Second Trunk Line is going to reinforce the monocentric alignment of the transport network in the MMR, which will likely cause further suburbanisation and metropolisation. Since construction has already begun, planning should mitigate the consequences using a strategy of transit-oriented development with a greater emphasis on functional mix around the newly emerging accessibility hubs.

6.2. Theoretical Background

Different strands within the spatial sciences discuss, on the one hand, the continuing de-concentration of population away from urban cores (“suburbanisation”) as well recent indications for its reversal (“re-urbanisation”). With regard to economic activity, both the concentration of economic activities and employment, often between regions (“metropolisation”), and the de-concentration, often within regions (“regionalisation”), are addressed but seldom together. Table 6-1 shows this categorisation that will be used in this paper, which is based on the literature discussion in the following paragraphs.

	De-Concentration	**Concentration**
Households	Suburbanisation	Re-Urbanisation
Employment	Regionalisation	Metropolisation

Table 6-1: *Dynamics of concentration and de-concentration of households and employment.*

6.2.1. Four Regional Dynamics of Concentration and De-Concentration

Suburbanisation describes the separation of residential location and workplace by a relocation of the residence from an urban core to a less densely populated area in the surroundings (Hesse and Siedentop 2018). Models that explain suburbanisation with transport costs have a long tradition in spatial sciences. In the monocentric model by Alonso (1964), for example, an improvement of transport infrastructure between the centre and the periphery leads in the medium to long run to an increase in city size through an expansion along the infrastructure, leading to suburbanisation and an extension of the commercial zones in the centre. An important precondition in the case of urban land uses is the observation that commuters have a fixed time budget that they are willing to devote to travelling, commonly empirically found to be slightly more than one hour across different spatial and temporal settings (Marchetti 1994; Zahavi 1979). Lehner (1966) has shown for Berlin that transport improvements and the diameter of built-up space have throughout the 19th and early 20th century indeed been directly correlated, each improvement in mass public transit allowing longer commute distances and opening up new areas around the city for residential development. However, while the (mostly rail-based) public transport infrastructure of this time on a regional scale promoted a structure of discontinuous settlements along a number of axes, only the spread of the car together with the expansion of road infrastructure from the middle of the 20th century on allowed the continuous extension of built-up area around cities. Digitalisation, working from home or while mobile and online shopping might further accelerate the spatial separation of workplace and residential location and deteriorate the importance of urban centres (Cairncross 1997). Even though the assumption of a single employment centre is a too crude simplification even for highly monocentric city-regions (Clark 2000) (see "regionalisation"), it can be concluded that regional transport infrastructure increases the "daily urban space", the number and scope of activities for its inhabitants, but in the long run also the potential locations for households and firms, potentially causing longer commute distances through suburbanisation and the large-scale separation and upscaling of urban functions.

At the same time, there has been a surge in studies detecting at least a slow-down of suburbanisation and an increased interest of (some groups of) households to remain in or return to the regional centres, and within them to their urban cores, often labelled "re-urbanisation". A stronger appreciation of urban (cultural) amenities (Glaeser, Kolko and Saiz 2001), a desire to co-locate with others of the same age group in times of demographic change (Simons and Weiden 2016), and the advantages of highly-accessible urban locations for dual-income couples and specialised knowledge workers in flexible employment conditions (Kohl 2014; Pütz 2015) are among the reasons identified behind this development in the case of Germany. This is not necessarily related to shorter commutes. Complex and atypical work mobility, especially reverse commuting to suburban workplaces and long-distance commuting between centres, are on the rise (Pütz 2015; Scheiner 2009; Heuermann and Schmieder 2018). Still, real estate rental and purchase prices remain the highest in urban centres compared to their surroundings, at least in most European cities, which is why students, young professionals, high-earners and creatives are so far the main protagonists of re-urbanisation (Hesse and Siedentop 2018; Scheiner 2006). Re-urbanisation also does not necessarily mean a change of lifestyles compared to "suburbia" in terms of dwelling type or mobility, as the examples of " inner-city suburbanization" described by Frank (2018) show. New regional transport infrastructure hence increases the opportunities to combine peripheral work and inner-city residential locations, particularly for high-income households, and increases the pool of potential employees for peripherally located firms. Inter-regional and long-distance commuting play a major role for this.

Regarding employment and innovation, the last two decades in regional sciences have brought forth a number of contributions that underscore the role of agglomeration economies, inter-regional competition and the interrelation between cumulative causation processes and network economies, which altogether account for an increasing concentration in particular of knowledge-intensive firms (Boix and Trullén 2007; Duranton and Puga 2004; Hoyler, Kloosterman and Sokol 2008; Florida, Adler and Mellander 2017). Notwithstanding digitalisation, face-to-face contacts remain the main channel for the transfer of tacit knowledge (Boschma 2005; Scott and Storper 2003; Gordon 2013). The strengthened role of knowledge in economic processes means that particularly spatial proximity to similar actors is valued more. "Metropolisation" describes the increasing concentration of economic activity, especially high-paid knowledge-intensive jobs in a few regions that are characterised by high international (air and high-speed rail) and internal connectivity, quality of life and a skilled workforce (Pumain and Rozenblat 2018; Krätke 2007; Meijers 2014) while other regions fall behind. There is hence an implicit connection to re-urbanisation. While the effects of interregional transport infrastructure on this development are ambiguous, as it always goes both ways and can potentially drain newly connected regions of their economic activity, inner-regional infrastructure is generally assessed to be conductive to regional competitiveness (Puga 2002) and advantages of agglomeration (Hesse, Schmitz and al. 1998). Aschauer (1989) has demonstrated strong multiplier effects of public infrastructure, particularly transport infrastructure, on regional productivity. The boundary between inner- and interregional infrastructure is not always clear, as each new piece of transport infrastructure also expands the (functionally defined) region. This entails the possibility that remote towns become integrated into the hinterland of a neighbouring centre in terms of workplace locations of the local population. While this is often seen negatively by local actors, it can also be seen as a tool to alleviate spatial economic disparities, as every commuting relation implies a reverse stream of income spent locally (Parr 2014). Nevertheless, there can also be effects of improved networks on the distribution of functions within regions. Generally, they are found to be in favour of the largest city, especially when it is small in population size ("borrowed size"), even though local population size remains the most important factor for endowment with workplaces and urban functions (Burger et al. 2014; Meijers, Burger and Hoogerbrugge 2016). Particularly Munich has been found to be a case of borrowing size within its region (Volgmann 2019).

While an increased premium for agglomeration means that firms still demand highly urban locations, diseconomies of agglomeration, such as overburdened transport systems, a lack of building space or a scarcity of skilled employees, which receive little attention in spatial sciences (Soja 2015), are among the most important reasons for firms to relocate to suburban settings ("regionalisation", (Growe 2012)) or even an overspill to more remote regions, as a study by Prognos just found for Germany (Prognos AG 2019). Garreau (1991) uses the term "edge cities" to describe new employment centres on the fringes of the suburbanising city—typically with high car-accessibility. Particularly, new hubs of international connectivity outside of cities, such as airports, have been nuclei of these developments, which increasingly provide both agglomeration and (relational) network economies to firms. In the long run, this can give rise to polycentric mega-regions (Hall and Pain 2006) with multiple employment centres and dispersed commuter relations, often difficult for public transport to serve. However, European edge cities are found to have not (yet) reached the size and importance of their American counterparts (Hesse and Siedentop 2018), also due to the greater role of public transport, whose sunk costs exert a preserving influence for existing centres. Even larger shopping outlets are increasingly looking for inner-city locations again as consumer behaviour changes (Förster et al. 2016).

It seems hence that despite similar tendencies (Sieverts 1997) the dissolution of urban and suburban in "regional urbanisation" as described by Soja (2015) for the US might not be fully adequate for the European context (Schmitz 2001: 161). Rather, "classical" residential suburbanisation still plays a major role (Hesse and Siedentop 2018; Simons and Weiden 2016), albeit in parallel to a selective re-urbanisation to the traditional cores (Adam 2019), while agglomeration economies mean an increased concentration of employment. Polycentric regions, where they have emerged, more commonly resulted from an already existing urban pattern of cities with similar size and in greater proximity to each other with the advances of transport technology.

6.2.2. Integrated Urban and Transport Planning as Sustainable Regional Development Strategy

In urban and regional planning, such polycentric, networked regions are often seen as a strategy—a normative potential to sustain a high degree of agglomeration advantages without having to bear too much of the costs of overcrowding ("Decentral Concentration") (Dehne 2005; Hague and Kirk 2003; Hall 2001; Boussauw 2018; Schmitt 2015). It is important to note that such concentration can occur on different spatial scales, from within-city to the regional scale. Such a decentral organisation of space is assumed to entail a range of social and environmental benefits as well, provided the urban areas are functionally and socially mixed, adequately dense, and interlinked by public transport.

Even though the direction of causality between built environment and travel mode choice remains disputed (Scheiner 2006), mixing and densification, especially through infill housing, is generally thought to encourage social cohesion and avoid long commutes and hence traffic and should always take precedence before transport infrastructure extensions. Particularly, if low-density areas are connected to urban cores, the "spatial drag" is reduced, which risks urban sprawl, longer commutes, more traffic and a decomposition of uses (Holz-Rau and Scheiner 2005). Hence, transport infrastructure extensions require cautious planning.

Recent advances in car technology, such as battery-powered cars, car sharing or automated driving will certainly alleviate some of the problems that individual transport causes in metropolitan areas, such as local emissions. The inefficient use of urban public space for (often parking) private cars will most likely, however, not change. Hence, public transport, particularly rail-based, still represents an important element for the functioning of cities and regions for those connections that cannot be covered locally by walking or cycling (Rode et al. 2014).

Nevertheless, in some cases it might be necessary to extend transport networks. If suburbanisation is happening anyways, it might be more environmentally friendly to channel it towards low-emission rail-based public transport rather than car-dependent settlements. Additionally, at least once that new public transport infrastructure has already been constructed, abandoning the generated urban development potentials would be an inefficient use of resources. In overheated rental and real estate markets, they can alleviate the burden on households.

Nevertheless, this requires a coordinated regional action that involves all affected municipalities, which might reject development for various reasons. Still, many decision-makers take a demand-side view and see mostly the advantages that new transport infrastructure provides for the existing population of a municipality, while too little attention is paid to new development potentials that are created. As a result, "integrated location and transport planning" or "transit-oriented development" (Holz-Rau and Scheiner 2016) are now predominant planning approaches to coordinate settlement development with public transport infrastructure investment to ensure that both residents and employees have at least the option to use public transport, and that transport infrastructure is used efficiently where it exists (Bertolini 1999) (see also "3. Materials and Methods").

6.3. **Case Study and Context**

The Munich Metropolitan Region (MMR), located in the south-east of Germany, is a functionally defined region consisting of the city of Munich as the main employment, business and administrative centre; its surrounding commuter belt and a ring of larger regional centres (among them Augsburg and Ingolstadt). The regional centres are characterised by an own commuter hinterland but exhibit strong functional relations with Munich in terms of business locations or common infrastructure, such as the airport. It has an area of about 26,000 km2 and a population of about 6 million, while its main centre, Munich, has a population of 1.55 million people in 2019 (München 2019).

The MMR is characterised by a strong local economy, with seven of the 30 firms in the main German stock index DAX located in Munich. Compared with other metropolitan regions in the country its unemployment rate is low and the purchasing power considerably above-average. It also regularly appears on high positions in urban quality of living ratings (Monocle 2018; Mercer 2019). This has resulted in continuous growth with respect to both population and economy in the last decades, and it is among the few German regions for which strong further population growth is expected in the future (Bayerisches Landesamt für Statistik und Datenverarbeitung 2018). The strong expansion of population and employment means that the MMR now suffers from growing pains. Housing development has not kept up with the pace of immigration to the region, and real estate prices are among the highest in Germany. This is despite strong suburbanisation that has occurred since the 1960s.

6.3.1. Public Transport in the MMR

In spite of the fact that the car manufacturer BMW is among the largest employers in the region, the modal split shows significantly above average and growing shares for public transport and cycling in both the core city Munich and the commuter belt, compared to other regions in Germany. As a result of rising motorisation rates in the 1950s, actors such as the local chamber of industry and commerce had recognised earlier than elsewhere the detrimental effects of car traffic on public space in the inner city and advocated public transport investments instead (Linder 1973: 157). Today, 15% of all journeys in the region, and 21% of all journeys in the city occurred using public transport, the figure rises to 51% for journeys to/from the inner city (Landeshauptstadt München 2010: 21-23). The figures for car-use (as driver) are 35%, 27% and 8%, respectively. Given the above-average usage of public transport, the system still exerts an influence on locational choices for a high share of the regional population.

The transport system—both road and rail—has largely been constructed in a monocentric alignment; there are few tangential connections, except between the regional centres. This transport network reflects the settlement patterns, and vice versa. The most important regional public transport infrastructure is the "S-Bahn"-network of suburban railway lines. The network was initially constructed as part of the preparations for the 1972 Olympic Games in Munich, which boosted the city's public infrastructure, by consolidating and upgrading varyingly used existing suburban lines and linking them with an east-west tunnel below the city centre. It is now used daily by up to 840,000 passengers (S-Bahn München 2019), near its capacity limits. Besides the S-Bahn, the MMR is served by an extensive regional train network (less frequent than the S-Bahn), local and regional bus lines, as well as underground and tram services in Munich (Figure 6-1).

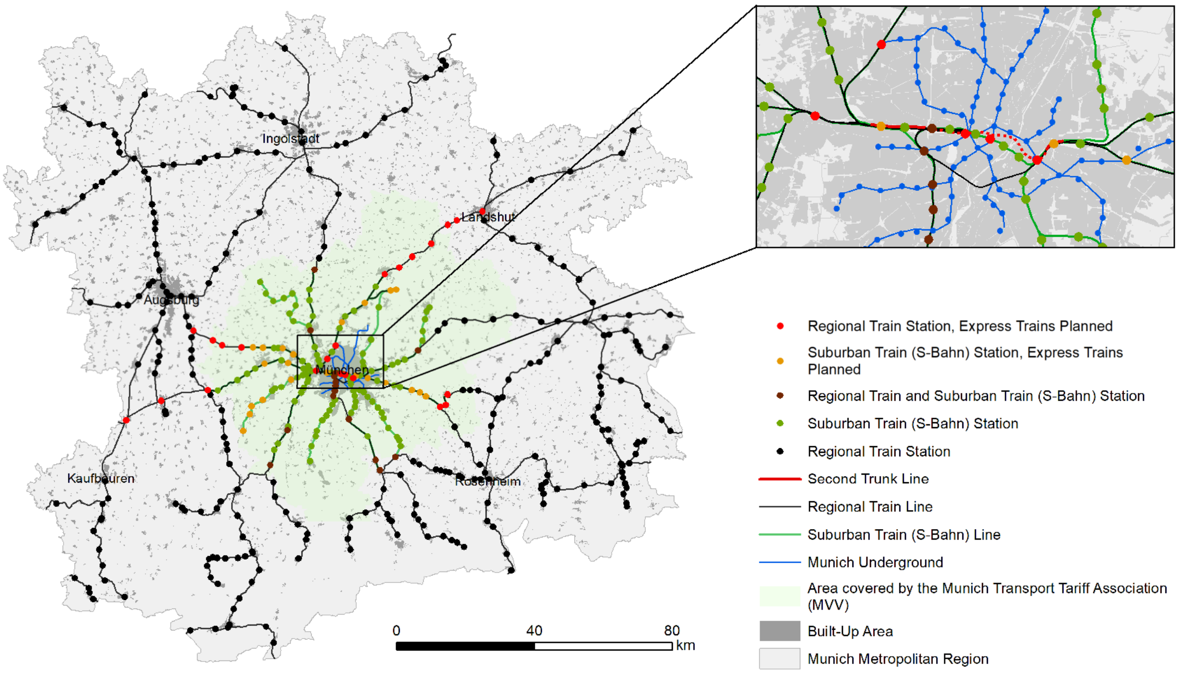

***Figure 6-1**: Current and future rail infrastructure in the Munich Metropolitan Region (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).*

6.3.2. The "Second Trunk Line" ("Zweite Stammstrecke").

After several decades of only piecemeal additions and improvements of the rail-based infrastructure, construction has now started on a significant alteration of the system, the so-called "second trunk line" ("Zweite Stammstrecke"). The 11.9 km long line—mostly in tunnels—is meant to double the capacity of the existing east-west line across the city centre that is currently used by all S-Bahn train lines. Already envisaged in the 1970s (Linder 1973: 173), it is scheduled for completion in 2028. The main aim is to improve the reliability and frequency of the S-Bahn system and to allow the introduction of express trains that skip several stations in the inner areas of the MMR. The express network will also stretch farther into the surrounding area than the existing S-Bahn network and will cover more of the metropolitan region, instead of 'only' the narrower city-region of Munich, currently included in the Munich Transport Tariff Association (MVV). The express trains mean that potential commute times to the city centre will be further reduced for a large number of suburban locations. The plan to construct the second trunk line has been strongly disputed by a number of public initiatives, who argue that that upgrading tangential connections would have been cheaper, faster, and more desirable (e.g. Baumgartner (2019); Arbeitskreis Schienenverkehr im Münchner Forum e.V. (2016)).

6.3.3. Previous Studies on the Relationship of Transport and Land Use in the MMR

Already the construction of the S-Bahn network had been monitored scientifically with respect to its consequences for settlement patterns. The most important works by Kreibich (1978) and Linder (1973) from the 1970s will be briefly summarised in the following (own translations). In his assessment of the likely development effects of the S-Bahn, Linder (1973) is very critical of the effects of mass transit on patterns of land use, and its capacity to reduce car traffic. He sees the S-Bahn as a structuring element of development of region-at-large and an attempt by the (then fully public) German rail operator Deutsche Bundesbahn (DB) to actively participate in the economic development and suburbanisation of Munich (p. 55). He describes the implementation of the then new (first) trunk rail line as "dictate" of segregation of employment, residential and recreational functions for the Munich region by DB, with the aim of a "pyramid construction of large-sized segregated economic spaces" (p. 203) for the sole purpose of economic growth for the region as a whole. Particularly, it encouraged economic concentration through increasing accessibility and locational advantages in central locations, especially when constructed radially (p. 198/203). The displacement of residential uses from the centre to the periphery in favour of commercial uses means displacement of the least with the most traffic-intensive use, creating unnecessary traffic that could be avoided with a closer allocation of spatial functions (p. 195/203). The capacity constraint of transport infrastructure in central locations hence means a real development barrier in the process of urban densification: Where disadvantages of growing congestion offset the advantages of central locations, a growing economy is forced to divert to other centres or the periphery, which might be more desirable in social terms (p. 196).

This view is shared by Kreibich (1978). His analysis of the settlement effects six years after the opening of the S-Bahn strikingly shows its catalysing effects on suburbanisation, with significantly higher population growth rates in towns along the new suburban rail lines. At the same time, he argues that firms are no longer required to operate branch offices in subcentres, instead being able to service a much wider area from the centre of Munich, reinforcing the monocentric structure of the region and leading to displacement of 50,000 residents from central areas between 1961 and 1974 (p. 294). Like Linder, Kreibich also criticizes the lack of tangential connections (p. 302). In being an instrument of regional economic growth, with detrimental consequences for interregional disparities, the S-Bahn "serves the continuing accumulation of capital in the centre of Munich and the preservation of the capitalist system".

More recent comparable studies have been conducted by Schürmann and Spiekermann (2011) for the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) and by Thierstein et al. (2016).

Schürmann and Spiekermann (2011) analyse the effects of four transport infrastructure projects (two rail and two road) in different German city-regions. For the MMR, they analyse the effects of the A96 motorway extension west of Munich completed in 1996. They find that the share of out-commuters to Munich along the corridor is highly correlated with the accessibility level of a municipality within the region, and that there are strong relationships between the accessibility level and the net migration of a municipality as well as the change rate of accessibility and migration surplus. Regarding employment, they find that the relationship between accessibility level and employment development is weakly negative but that improvements in accessibility are correlated with employment growth (particularly for distance- and car-based accessibility indicators). Overall, they identify a strong relation between accessibility levels, land values and urbanisation. Interestingly, their data also shows that the establishment of the new Munich airport north-east of Munich in 1992 seems to have had even stronger effects on employment and population in the respective surrounding municipalities than the A96 corridor.

A study of household, workplace and mobility choices in Munich by Thierstein et al. (Thierstein et al. 2016; Zhao, Bentlage and Thierstein 2017; Kinigadner et al. 2016) has highlighted the need for differentiation between population subgroups and their motivations for residential and employment location choices. In a sub-project, Zhao, Bentlage and Thierstein (2017) demonstrate for example that knowledge-workers show differing patterns of the use of space according to their knowledge-base (as identified by Asheim (2007)). While "analytic" knowledge workers – e.g. in the domains of engineering – show a higher willingness to settle in a suburban setting and a preference for car-oriented transportation, "synthetic" and "symbolic" knowledge workers, e.g., in the art and cultural industries, show a stronger preference for urban locations and for active-mode transportation. The study also underlines the need for a better jobs–housing balance in the municipalities of the region as a strategy to reduce commuting distances, as well as an improvement of urban amenities in smaller municipalities (Kinigadner et al. 2016).

Finally, the Swiss Federal Office for Spatial Development (ARE (2004)) has studied the impacts of the opening of the suburban rail network in Zurich 1990, which is comparable to Munich in terms of its economic structure. The study likewise finds evidence for population growth in the area served by the system but even stronger growth in some unaffected municipalities. In terms of employment, areas that have not benefitted from a travel time decrease to the centre have suffered from losses, as well as areas with a strong increase in accessibility in already good starting positions. No clear overall tendencies could be observed. The study highlights the conjecture of three forces influencing local population and employment growth, transport effects, (endogenous) potentials and actors, and recommends stronger collaboration between municipalities, landowners and rail operators to activate building potentials in proximity to stations.

In sum, past studies on the effects of transport infrastructure improvements on settlement structures in Munich tend to find strong relations to suburbanisation, the large-scale segregation and concentration of urban functions and metropolisation but little indications for a connection to re-urbanisation or a regional dispersion of economic activity. The effects seem to weaken with time. The MMR seems, at least until now, as a whole, not to be characterised by the "disappearance of traditional suburbia" or a "blurring of the boundary between urban and suburban" (Soja 2015: 374-375), nor have major "outer cities" materialised in low-density suburbs that could rival the traditional urban cores. The studies hint at the conclusion that the monocentric alignment of transport infrastructure, along with other planning policies to protect the traditional urban cores could be responsible for this.

6.4. **Materials and Methods**

The fourfold division of the paper is also reflected in the methods. To answer the first research question, we analyse recent commuter data for the MMR between 2005 and 2018 by the German Federal Employment Agency, using descriptive statistics. Commuter data is very useful to identify concentration and de-concentration processes of households and employment, as it always encompasses both residential and work locations (Pütz 2015).

For the second research question, we use a gravitational accessibility model of population. Gravitational accessibility is a measure to describe the cumulative "possibility of interaction" (Hansen 1959) measured through the number of people (or jobs, amenities etc.) that can be reached from a certain location, while more distant destinations in terms of travel time are weighted less than those in greater proximity. We use an exponential distance decay function in the form of

$$Gravity[i] = \sum \frac{W[j]}{e^{\beta \times d[i,j]}} \quad \text{(eq. 6-1)}$$

where Gravity [i] is the Gravity index at location i, W[j] is the weight of destination j, d[i,j] is the travel time between locations i and j, and β is the exponent for adjusting the distance decay (see (Geurs and van Wee 2004) for a more detailed description). The gravitational approach has a long tradition in land use-transport interaction modelling and accessibility analysis (e.g., Geertman and Ritsema Van Eck (1995); Rich (1978)), as it is assumed to model interactions and travel likelihood closely.

The distance decay is calibrated using actual commuter data from the MMR for 2018. The share of out-commuters to Munich on all out-commuters in a municipality halves after about 20 minutes of public transport travel distance between the municipality and Munich, resulting in a decay factor of 0.033 for the exponential function (R2 = 0.78), in line with a range of other studies of regional commuting relations (e.g. Ahlmeyer and Wittowsky (2018); Geurs and van Eck (2001); Rosik, Stępniak and Komornicki (2015)). The model includes 512 rail stations and their interconnections in the MMR. It encompasses not only the S-Bahn network, which so far covers only Munich and its hinterland but not the regional centres, but also the regional train network that stretches across the entire metropolitan region, and the underground network in Munich. The travel time data was gathered manually from the travel information of Deutsche Bahn (DB 2020) for a Tuesday morning in the timetable period of 2019 without construction works. The data for 2028, after the opening of the second trunk line, was estimated based on the currently planned operational programme as published on the official project website (DB Netz AG 2019). No new stations will be added through the project, the new express lines will only serve – some – existing stations.

Gravitational accessibility modelling has a number of potential weaknesses. To circumvent the self-potential bias in cell-based gravitational accessibility analyses (Bruinsma and Rietveld 1998), we followed the method of Stępniak and Jacobs-Crisioni (2017) and calculated the average weighted distances from 100x100m population grid cells of the 2011 census (Statistische Ämter des Bundes und der Länder 2011) to the nearest station included in the model to correct for differing internal population distributions. These population figures are then used as weights of the stations. A common challenge of accessibility models is furthermore a negative bias towards the fringes, unless a buffer zone is included. Hence, we added a buffer zone of 518 stations in a 2-hours travel time buffer around the MMR. In Austria, however, only a 1 x 1 km population grid could be used to derive station weights. The accessibility calculations were carried out for 2019 and 2028, and the results compared. No changes in the distance decay parameter or the population distribution were assumed. An important constraint of the model is that it does not reflect differences in service frequencies of the connections included and that transfer times can only be modelled very crudely. For the model, a fixed threshold of 120 minutes as minimum frequency was chosen to determine whether a connection is included or not, and transfer times were generally assumed to be two minutes, as public transport in the core areas of the region is quite frequent. Here, agent-based modelling provides more realistic results on the level of individual users of the system. Another important qualification must be made regarding the costs used in this paper: It focuses on time-costs only, while monetary costs are important determinants of public transport use as well. In the course of the "Zweite Stammstrecke" project, it is however mainly the temporal aspect that will change. The new lines will be included in the existing transit tariff of Munich. We hence refrained from including monetary costs in our analysis.

For the third step, we gathered additional data on the functions around the 512 stations, namely demographic, employment and land use data in a 700 m radius. Such 700 m radius is typically seen as a distance that residents in urban and suburban settings on average are willing to walk to a higher-order public transport stop like a train station (Korda and Bischof 2005). Where these radiuses overlap, they were cut along the equidistant line between the stations to avoid double-counting. In detail, we collected data for three indicators, the population size, the number of firms, as well as the combined number of retail, leisure and public facilities—henceforth called "facilities". Firms and facilities data originate from the company database Bisnode (Bisnode 2016), which lists more than 400,000 firms for the MMR. Facilities were identified according to the SIC classification included in the database (SIC codes 52 to 59 for retail, 78, 79 and 84 for leisure and 91 to 99 for public facilities). In a few cases, the values for shopping and leisure facilities were manually adjusted to adequately represent mass attractors, such as football stadia, large shopping centres and important sights.

It is a basic principle of integrated urban and land use planning that the accessibility a public transport station provides should be in balance with the density of functions around the station. A station with high accessibility (frequent and fast connections to a lot of potential opportunities) should not be surrounded by greenfields—this would be an inefficient use of the public transport resources. Vice versa, dense urban areas should be served by highly accessible public transport stations to avoid car-dependent settlement structures. Hence, planning should not allocate too many functions to stations with low accessibility, or areas far away from public transport, and encourage development around highly accessible but underused transport nodes. A basic conceptual model that describes this relationship is the "node-place-model" by Bertolini (1999) that suggests aiming for a balance of "node" (accessibility) and "place" (functional density) at each station. It allows visually to identify "unsustained nodes" and "unsustained places" (stations with an accessibility surplus over the local density of functions and vice versa), as well as "dependent" and "stressed" stations, that are balanced but in danger of inefficiency or overcrowding. The model has been operationalised and tested in various settings (e.g. Gilliard et al. (2018); Peek, Bertolini and De Jonge (2006)) and several additions have been proposed to derive more detailed station typologies (e.g. Caset et al. (2019)). For this paper, we assumed the accessibility values from the second step as node values and the combined functional data (population size, firms and facilities) as place values.

As a fourth step, to derive policy recommendations, we used the indicators and additional data to construct six variables for a cluster analysis:

- Functional Density (or "Place Value", as described above).
- Functional Surplus: The surplus or deficit of local functional density compared to accessibility.
- Residential Surplus: The surplus or deficit of local population size compared to jobs and facilities.
- Accessibility Change (2019–2028).
- Densification Potential.
- New Building Potential.

The densification potential was calculated by determining the area within the 700 m radius around the station that is classified as "built up" in the land use cadastre (Bayerische Vermessungsverwaltung 2014) and dividing it by the place value. The variable hence describes the efficiency of the use of space, i.e., the space needed per point of place value. We assumed as new building potential all areas classified as agricultural or forest, unless they are protected.

The data for all indicators except the new building potential were divided by their maxima and transformed using a square root function to smooth out outliers. For the functional data, this was done separately for population size, firms and facilities and later summed up. All indicators were then normalised on a 1 to 100 scale. The variables were used for a K-means clustering approach to identify groups of similar stations. A solution with seven clusters was chosen as appropriate solution.

6.5. Results and Discussion

6.5.1. Structure and Dynamics of Commuting Relationships in the MMR 2005–2018

The first research question deals with the current structure and recent dynamics of commuter relationships. Figure 6-2 shows the strongest commuting relationships between municipalities in the MMR (250 and more commuters), Figure 6-3 shows the strongest changes of commuter relationships between 2005 and 2018. No major infrastructure works have been completed during this phase. Aggregate commuting has decreased between 13.5% of all pairs of municipalities, but in these cases only in small absolute numbers. Figure 6-3 hence shows only relations where the aggregate number of commuters has increased by more than 150.

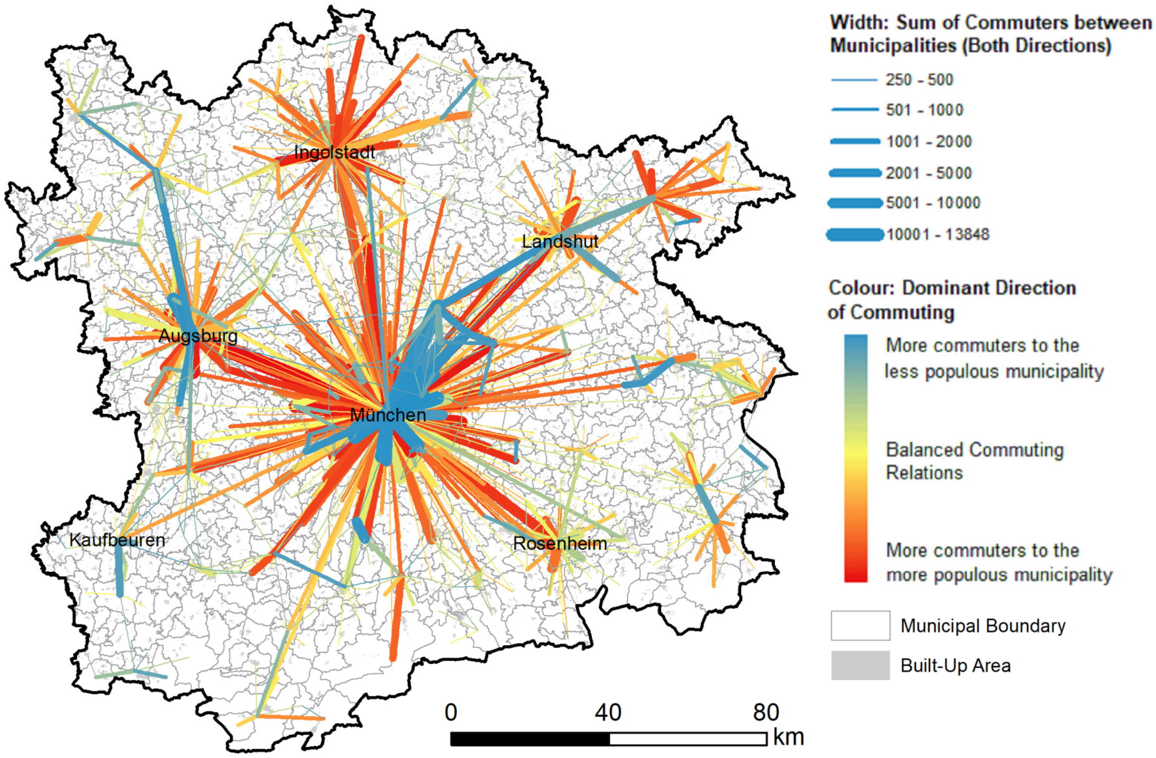

Figure 6-2: *Strongest commuting relations in the MMR in 2018 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Bundesagentur für Arbeit).*

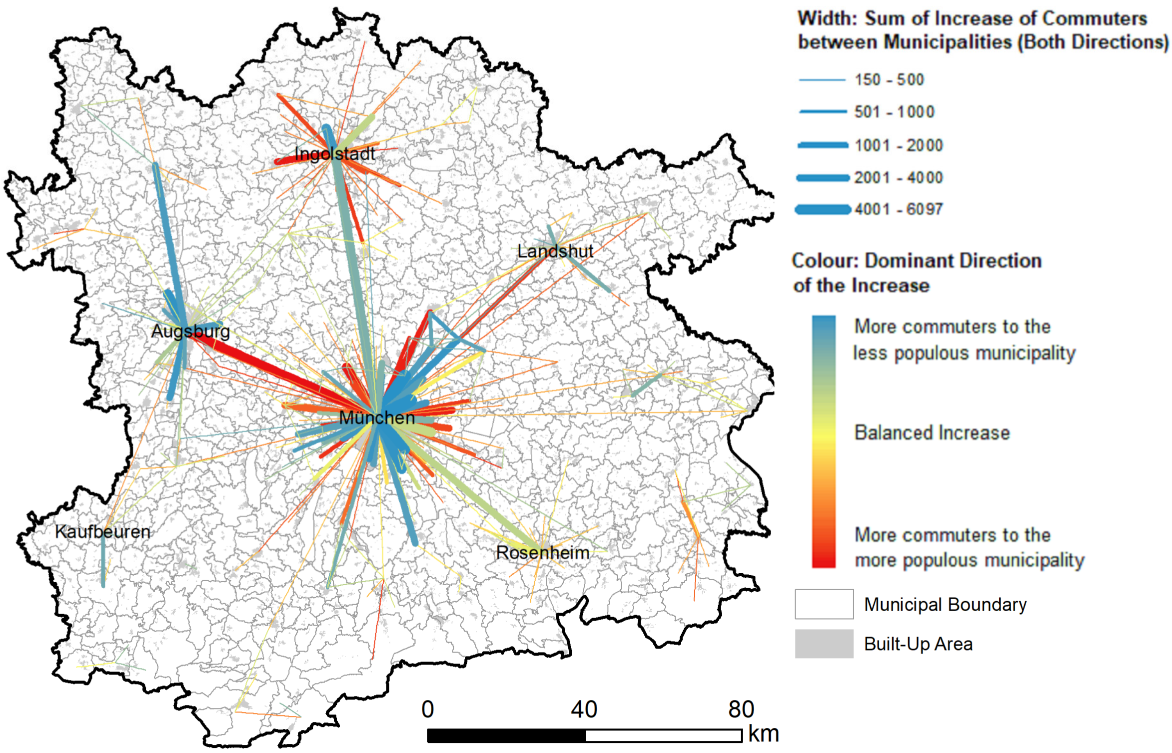

Figure 6-3: *Dynamics of commuter relationships in the MMR between 2005 and 2018 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Bundesagentur für Arbeit).*

Commuting relationships in the MMR still show a fairly classical pattern of core–periphery. The city of Munich and, to a lesser degree, the regional centres of Augsburg and Ingolstadt are dominant centres of in-commuting, which shows the degree of metropolisation and suburbanisation in the region. However, some of the municipalities directly bordering on Munich, particularly to the south and north-east, exhibit a commuter surplus from Munich. All these municipalities are well-connected to Munich by rail-based public transport. These relations also show the strongest dynamics during the last 14 years. The most remarkable change has occurred between Munich and its neighbouring municipality Unterföhring to the north-east. The number of out-commuters from Munich to Unterföhring has risen from 6948 to 11,300 in just 14 years, while the reverse direction is only travelled by 2700 commuters a day (2005: 1703). This means that now the strongest commuter flow in the MMR is no longer directed at Munich as in 2005, but away from Munich to one of its suburban neighbours. The change is likely driven by a high number of media and insurance companies located there that have exhibited strong job growth. The town is also located on the axis between Munich and the airport, which is another job motor in the region. It seems however that employees at firms in Unterföhring are not willing or able to relocate there and instead chose to commute from Munich, despite slightly higher rental and real estate prices, which points to an increasing role of urban amenities for employees in knowledge-intensive firms.

The weak position of Augsburg, the second largest city in the region, comes as a surprise: There has been a strong increase in out-commuting to almost all neighbouring municipalities during the last one and a half decades. Augsburg is now the number one commuter origin for Munich and could functionally become a large suburb in the future, as there are no signs of a change in dynamics or an increase of commuting in the reverse direction. Commuting between the other regional centres and Munich has also strongly increased but in a more balanced way. Not included in the figure, but likewise with above-average increases, are commuting relations between the regional centres in the MMR and those of neighbouring regions, particularly between Munich and Ingolstadt, on the one hand, and Nuremberg, on the other, confirming the findings of Pütz (2015).

In total, Munich and Ingolstadt still gained new in-commuters from the fringes of their commuter zones, while the commuting relationships with some of their immediately surrounding municipalities are increasingly characterised by a reverse commuting, while overall commuting distances continued to rise. This is in line with previous literature for the Munich case (Guth et al. 2011; Schmitz 2001). It is thus fair to still speak of a rather monocentrically-organised region, with signs of polycentricism immediately around the major regional centres. There are two main restrictions to this argumentation, however: The latter can be interpreted as a phenomenon not entirely different from the past, just an upscaling – polycentric development, albeit weak – has happened within the city-limits before (e.g. Krehl (2015)), and only now that it exceeds the administrative boundaries, it is also visible in the commuter data. Second, and more importantly, tangential commuting relations still play almost no role in the MMR. Among the top commuting relations, there is none that is not directed either to or from one of the major centres Munich, Augsburg and Ingolstadt. These are also still the commuting relations with the strongest growth. Only the 144th relation (Erding–Freising, 1100 commuters) is tangential. This is likely caused by the airport, which is located on the border between the two municipalities and shows its capability to act as nucleus for economic activity.

Regarding our first research question, we conclude that, indeed, commuter relations suggest a growing role of out-commuting from the major centres of the region to municipalities in the vicinity and therewith highly urban and central residential locations combined with suburban employment (re-urbanisation and regionalisation). However, the majority of commuting relations still conform to the traditional regional core–periphery dichotomy. In addition, the new employment centres in the surroundings of Munich, Augsburg and Ingolstadt have so far not been able to attract substantial tangential commuting relations from their other neighbours, which might be due to the monocentric structure of the public transport system.

6.5.2. Rail-Based Public Transport Accessibility and Accessibility Changes through the Second Trunk Line

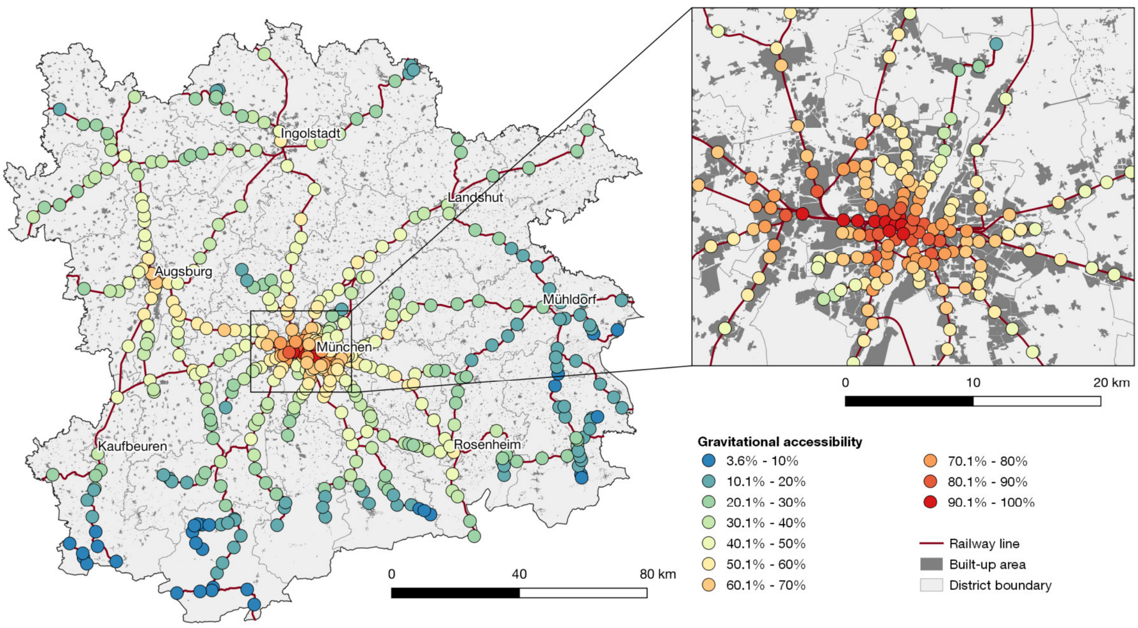

***Figure 6-4**: Accessibility of population with rail-based public transport at railway stations in the MMR 2019 (Munich main station = 100%) (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).*

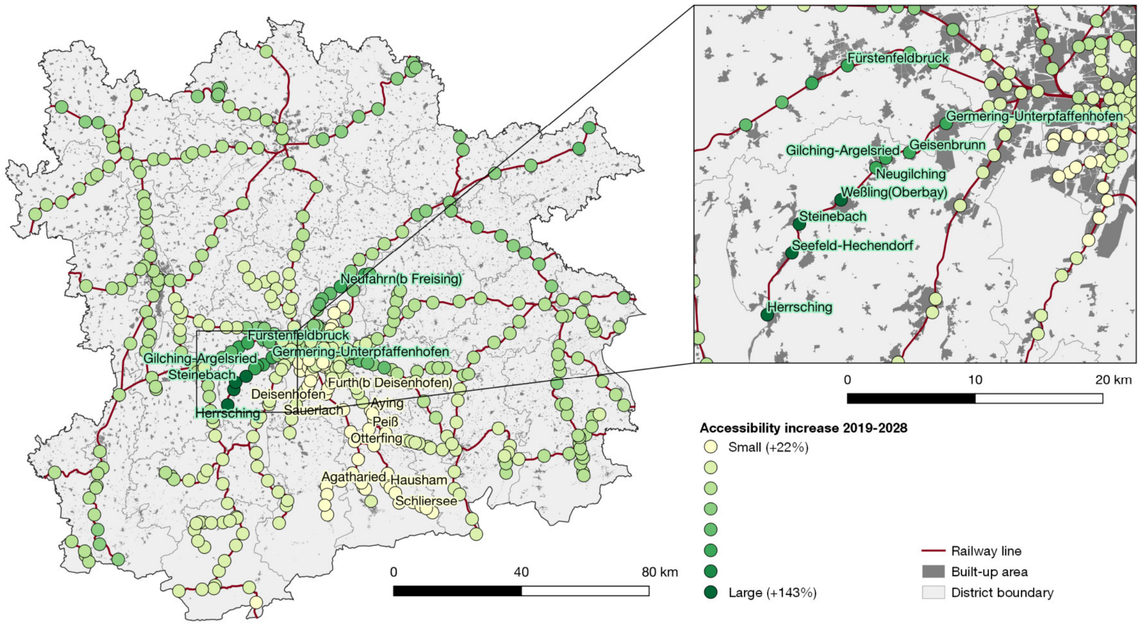

***Figure 6-5**: Change of accessibility of population with rail-based public transport at railway stations in the MMR 2019–2028 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).*

Figure 6-4 shows the clear accessibility gradient by rail-based public transport in the MMR. The most accessible station is expectably Munich main station, from where travel times to most other destinations are shortest (set as 100%). The first 48 of 512 stations in terms of accessibility are located in Munich proper, among them all stations along the first S-Bahn trunk line. Despite the inclusion of a large buffer zone, the stations to the south, close to the Alps and the Austrian border, show the lowest accessibility values, also because often they are located in "dead-ends" of lines. The regional centres Augsburg, Ingolstadt, Landshut and Rosenheim clearly exhibit smaller accessibility maxima, but these do not come close to the values that even suburban stations around Munich show.

Figure 6-5 shows the increases in gravitational accessibility induced by the construction of second trunk line. The east–west orientation of the new infrastructure means that improvements of accessibility are foremost located in these sectors around the city. The stations in the south of the region will profit relatively little, even though they are currently already characterised by low absolute accessibility levels. Nevertheless, it can be seen that all stations in the region profit from an increase of accessibility of at least 22%, even where there will be no direct lines using the new infrastructure, due to trickle-down effects throughout the region. Munich main station is still the point of the highest accessibility, and it is among the stations with the highest absolute accessibility increases, which shows the reinforcing effect of the second trunk line on the monocentric regional structure and confirms our hypothesis. Other stations along the second trunk line can also strongly improve their rank position.

However, in relative terms, suburban stations along four corridors to the west, north and east of the city are to gain most, albeit from a low previous level. Some of the municipalities to the west of Munich, currently showing a strong commuter-deficit, will experience a doubling of their accessibility, higher than some peripheral parts of the city of Munich proper.

The strongest accessibility gain was determined for the small town of Weßling, the designated first stop of a planned express line beyond the city centre.

The analysis shows that the strongest effects are highly selective and affect only some sectors of the public transport network. The effects depend highly on the scheduled services. It also shows that the effects quickly attenuate with distance, assuming a commuting-related distance decay factor. Still, some smaller regional centres that were so far in greater relational distance to Munich, such as Kaufering, Buchloe and Mering to the west of Munich, will receive a direct connection to the very centre of the city and partially fall below the critical commuting time threshold of slightly more than half an hour. Methodologically, the analysis shows the merit of gravitational accessibility analysis for visualisations.

As accessibility and land values are strongly related, the map can also be read as a projection—or at least a spatial perspective—of likely demand changes on the land market. Based on the previous experiences in the region as described in the literature review and the results of chapter 3.1, it can be assumed that particularly the west of Munich will undergo another wave of suburbanisation that will intensify the pressure in the existing commuter belt and extend it further westwards to include the smaller regional centres there. At the same time, the monocentric alignment of the second trunk line means that it will increase the potential customer and employee base of firms in highly central locations, contributing to further segregation of functions and an extension of the commercial zone in Munich.

However, planning can and should set the framework for this development and try to work towards greater regionalisation of economic activity. In the following chapter, we develop a station typology with policy recommendations, which not only includes accessibility but also local potentials and small-scale mix of uses.

6.5.3. Comparison of Accessibility Levels and Functional Density around Railway Stations in the MMR

Figure 6-6 compares the accessibility ("Node") and combined functional density of population; firms; and public, leisure and shopping facilities ("Place") for all 512 rail stations in the MMR in 2018. It shows that there is a broad but significant relationship between node and place values (R2 = 0.41), and a high number of stations can be classified as "balanced" (termed "accessible" in the stricter sense by Bertolini (1999)). This means that the larger the number of people that can reach a certain station in a short amount of time, the higher the density of functions around it, which is a characteristic of a sustainable transport system (see "methods"). The stations categorised as in "Stress" are all located in the inner city of Munich, where a combination of high density and accessibility can lead to overcrowding. At the same time, this is a sign for the still highly monocentric transport and settlement structure of the region.

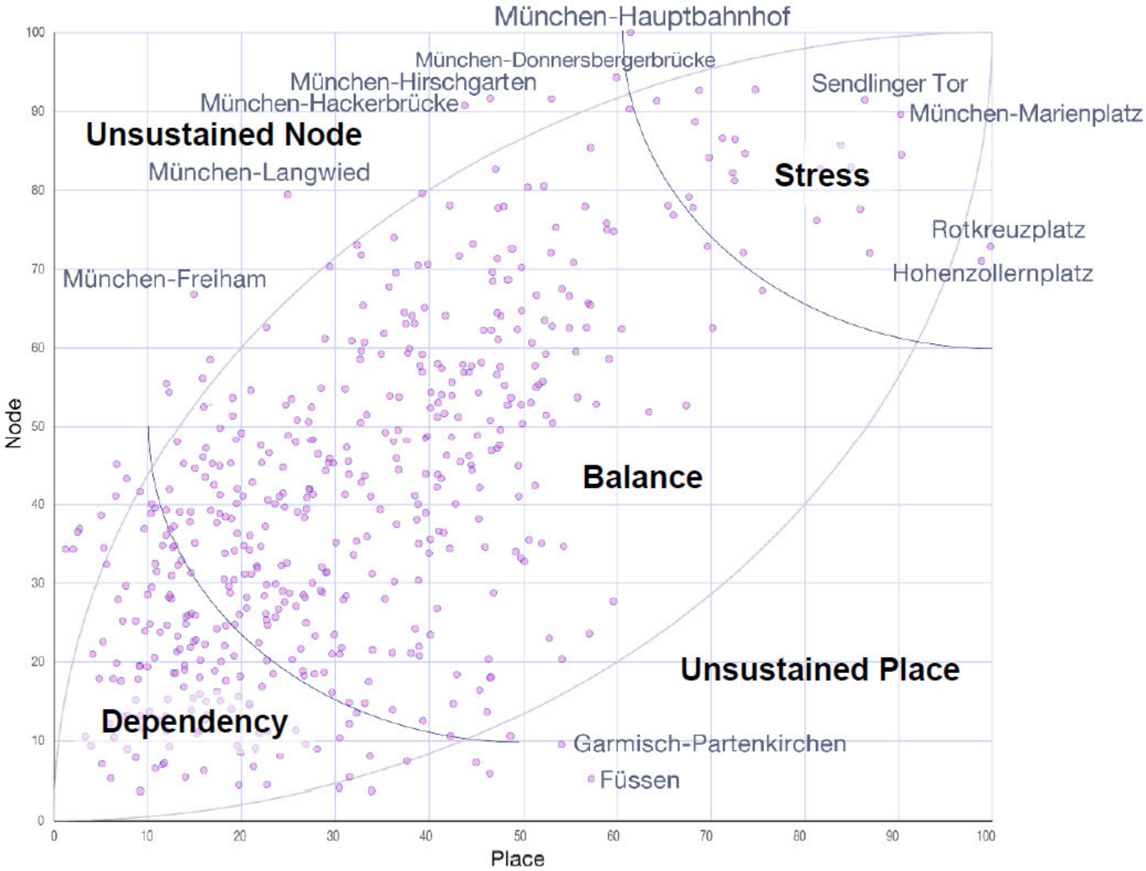

***Figure 6-6**: "Node-place diagram" for the Munich metropolitan region in 2019 (Source: own work).*

A few stations are located outside of the balanced category. On the one hand, there are "unsustained places", with high functional density but low accessibility. Many of them, such as Garmisch-Partenkirchen and Füssen, are located in the Alpine region south of Munich, where, as described earlier, the difficult topography means that rail lines are not interconnected. However, unsustained places can also be found in the city of Munich proper. Two inner-city sub-centres, Hohenzollernplatz and Rotkreuzplatz, exhibit a much stronger functional density than their accessibility levels would give reason to expect. Within Munich, accessibility levels quickly attenuate with distance from the east–west trunk line. Neither the first nor the second trunk line serves these stations, meaning that they will only profit indirectly from future accessibility increases and not more than other, balanced, stations. This shows that de-concentration of activities into smaller local clusters can at least be identified on a within-city scale and does not necessarily correspond to public transport infrastructure.

The "unsustained nodes", on the other hand, show a less clear pattern. They are distributed across the entire region and are more dependent on individual local conditions, like protected and irreclaimable areas. Figure 6-7 shows the spatial dimension of the node-place diagram.

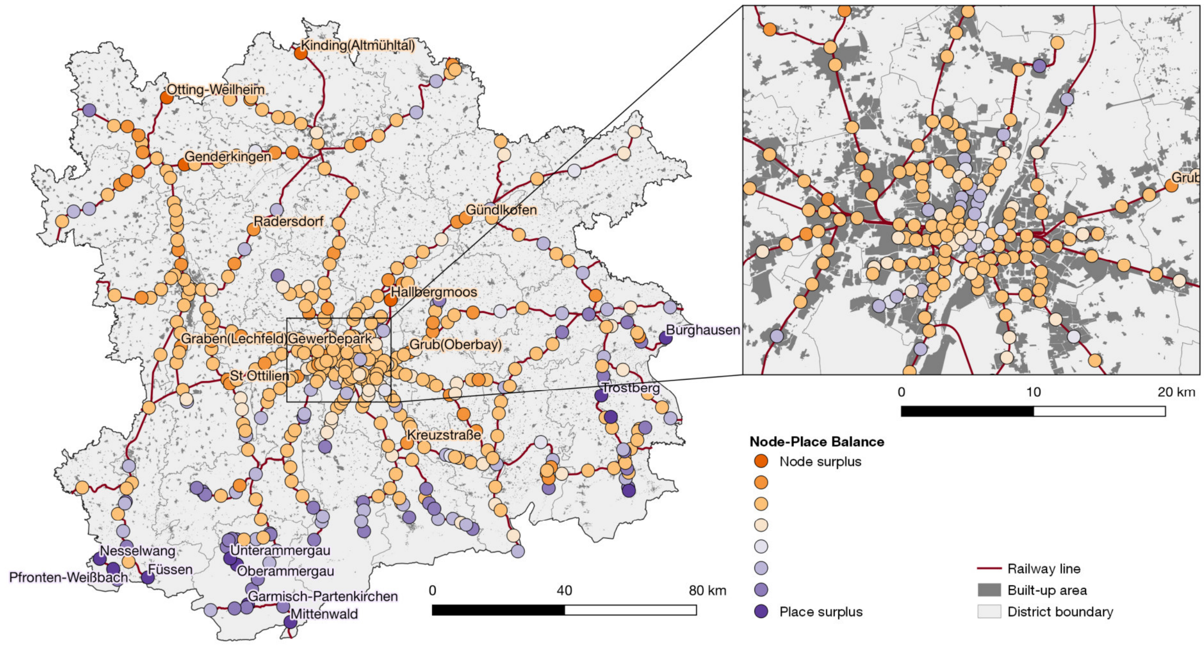

Figure 6-7: *Balance of accessibility ("Node") and functional density ("Place") around railway stations in the MMR in 2019 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).*

The impact of the second trunk line means that a number of stations will move out of the "Balance" into the "Unsustained Node" category, for which an increase of functional densities should accordingly be sought. It should be clear however that the model should never be taken as strict blueprint but that the accessibility-induced development potential must always be harmonised with other local requirements, such as environmental protection or conservation.

The fact that the model focuses on railway stations brings with it advantages and disadvantages: On the one hand, railway stations in urban areas are often surrounded by derelict railway land and disused production sites, as a result of the structural change to the knowledge economy. These represent prime building land. The proximity to high-quality public transport means that this land is a convenient location for car-free or car-reduced neighbourhoods. On the other hand, noise from railway lines is a challenge to be adequately dealt with by an appropriate allocation of uses and modern techniques of acoustic protection. For land immediately adjacent to railway lines "urban production" and similar new forms of small-scale manufacturing might also be a suitable use.

Nevertheless, the node-place model in its basic form only uses an aggregate perspective on "Place". However, previous studies point at the importance of small-scale mixing of uses to avoid wasteful commuting and unnecessary traffic (see "Theoretical Background"). Disintegrating the combined place indicator into its sub-dimensions allows to include this dimension into the analysis. A balanced distribution of residential and commercial uses at a station hints at advantageous conditions for local inhabitants to avoid longer commutes.

When comparing residential density at stations with job and facility density (Figure 6-8), the CBD in the inner-city of Munich can be clearly identified. In the surroundings of the most central stations, Marienplatz, Karlsplatz (Stachus) and the main station, firm locations and facilities strongly outweigh residential locations. Marienplatz, commonly considered the heart of the city and hosting the city hall, is endowed with one of the highest absolute number of firms but ranks only at 237th place in terms of population size. The fact that the stations of highest accessibility correspond with those of the highest imbalance between residential and commercial uses corresponds to classical models of regional land use distributions (Alonso 1964). Clearly, the S-Bahn serves the hotspots of metropolisation in the region.

Interestingly, a number of stations outside of the traditional urban centres show a strong commercial surplus as well, most noticeable around the airport of Munich, at the major suburban campus of the Technical University of Munich in Garching and at Graben (Lechfeld) Gewerbepark, where a major online retail company has located its regional distribution centre. It seems that mainly strong individual actors, both public and private, are able to initiate and sustain a regionalisation of employment.

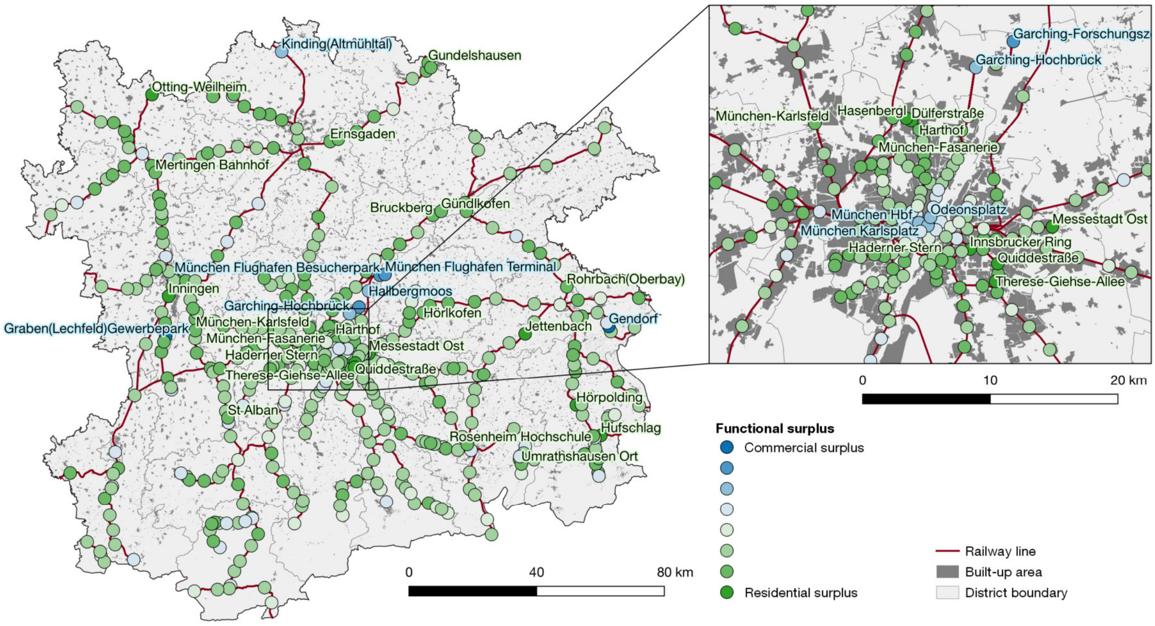

Figure 6-8: Surplus of residential or commercial (firms and services) uses at railway stations in the MMR 2019 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

In a few cases, the settlement areas meant to be served by stations are located more than 700 m away from the rail line, e.g., due to technical constraints during the construction phase. In these exceptional cases, the comparison of node and place values yields strong outliers. On the one hand, this can be desired in terms of the model purpose, i.e., it shows the need to establish a new centre around the station. However, in these cases, it might be more useful to try to shift the station in greater spatial proximity to the built-up area.

6.5.4. Policy Recommendations Based on Cluster Analysis

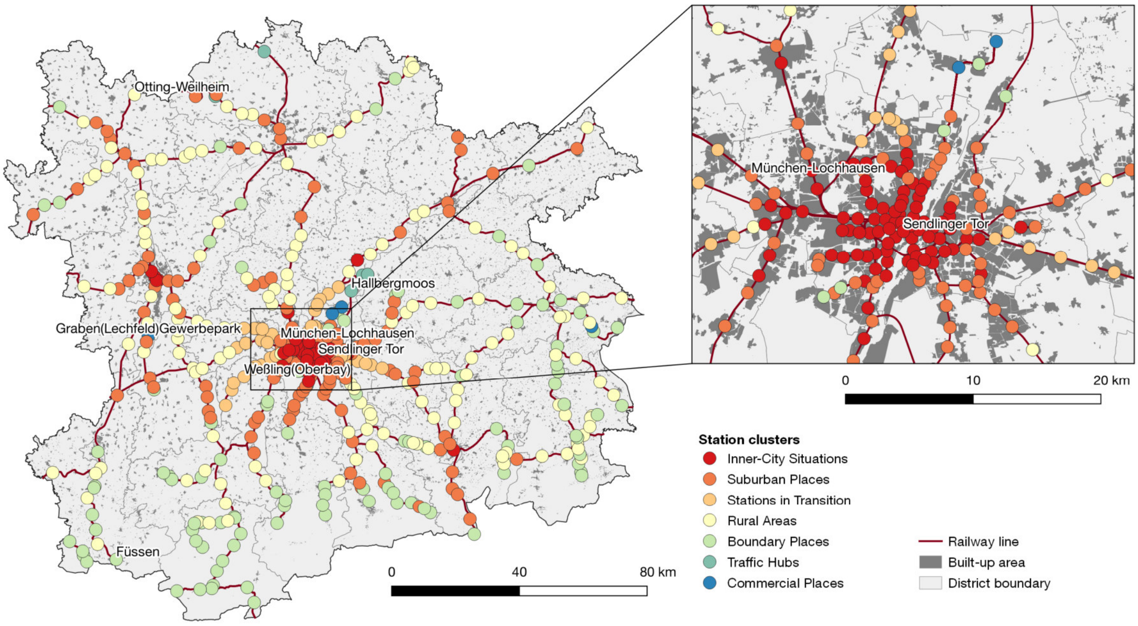

Figure 6-9: Spatial distribution of the station clusters (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

To integrate the different steps of our analysis, accessibility change, balance of accessibility and functions, as well as balance of residential and commercial uses, and to combine them with densification and new building potentials, we perform a cluster analysis (see "Methods"). We identify seven clusters of stations that show strong similarities with respect to the input variables and that allow the formulation of policy recommendations. Figure 6-9 shows the spatial distribution of the clusters, Table 6-2 shows the average values of the variables used for each cluster.

Cluster Name	Number of Stations	Functional Density	Functional Surplus	Residential Surplus	Accessibility Change	Densification Potential	New Building Potential
Inner-city Situations	88	60,53	–19,58	26,57	18,92	26,75	1,36
Suburban Places	130	31,94	–31,90	42,48	23,14	38,22	17,71
Stations in Transition	35	39,09	–35,44	46,49	57,29	35,64	20,50
Rural Areas	145	15,31	–42,82	49,39	28,32	37,10	65,91
Boundary Places	105	32,75	52,97	28,76	24,47	36,44	30,17
Traffic Hubs	5	8,76	–67,94	–43,92	48,68	25,26	15,53
Commercial Places	4	10,54	–46,98	–70,67	21,53	73,61	43,56

Table 6-2: Average values of the clustering variables for the seven clusters of stations.

The clustering results in five groups that can be broadly allocated spatially. (1) Inner-city Situations show the highest functional density, a relatively low residential surplus and almost no new building potential. Since many can be found in the "stressed" category in the node-place diagram, solutions should be sought to relieve congestion in the most affected stations, such as new tangential connections on the city scale. For those stations that show a high functional surplus, the focus should be on transport improvements rather than densification measures. (2) Suburban Places are characterised by a high residential surplus, proximity to a larger city, medium functional densities and average densification and new building potentials. Their mono-functionality means longer than necessary commute distances, indicating a potential to improve the local mix of uses and encourage regionalisation of economic activities. The strongest drivers of such a regionalisation are individual strong public or private actors, such as universities, research facilities, larger firms or cultural facilities that are able to set in motion a self-reinforcing development. (3) The "Stations in Transition" can be seen as a subgroup of Suburban Places but with high accessibility gains until 2028. Despite the potentially negative effects on travel distances, the new development potentials should be used to avoid further car-oriented suburbanisation. A mixing of land uses should be targeted for from the beginning. (4) Rural areas clearly fall short of the functional density in the suburban areas but exhibit the highest residential surplus and new building potential. Despite this potential, further residential densification should not be considered, as overall accessibility is low and distances to employment centres are long. More local jobs would be advantageous but are not to be expected, given the tendency for agglomeration. Stations in this cluster should be considered for relocation where they are further away from the centres of the settlement areas they are supposed to serve or for merging with other nearby stations when no significant disadvantages are to be expected. (5) Boundary Places are stations with a strong surplus of local functional density, compared to the low public transport accessibility. They show a greater mix of housing, jobs and facilities, and a medium functional density. Boundary Places can be addressed as self-sufficient areas that are not strongly integrated into regional transport networks. The focus should be on linking them with each other to improve regional connectivity without risking that they become suburbanised.

While the first five clusters consist of a higher number of stations, two very small clusters with specialised profiles emerge: Transit Hubs and Commercial Places. (6) Transit Hubs are characterised by a very low functional density and, accordingly, a deficit of functional density to accessibility. Typically, they are isolated stations with the main purpose of providing interchanges to connecting bus lines, without serving local uses that could be reached by walking. The lack of functions around them represents a lost opportunity in terms of both an efficient public transport system and an economic use of space, if it means that other areas are developed instead. Stations with little surrounding activities are also often perceived as unsafe. Given their high accessibility to urban centres and in many cases also the airport, transit hubs represent an important untapped reserve for substantial new development. They are candidates for the establishment of regional sub-centres and drivers of a regionalisation of employment. (7) Commercial Places show almost no residential uses in their surroundings and an overall low functional density but high development and new building potentials. Often, they are in the vicinity of a single facility that they are meant to serve. In some cases, this might only be used during certain times of the week, e.g., sports stadia.

Where suitable, Commercial Places could be supplemented by local residential uses to reduce commuting distances, as well as smaller businesses to avoid mono-functionality. Where space for this is missing, finding more efficient solutions for the often large parking areas around these stations might provide a way forward. Table 6-3 sums up the cluster characteristics and policy recommendations.

	Characteristics	Policy Recommendations	Examples
Inner-city Situations	High functional density Second highest functional surplus Very little new building potential Station overload by transfer passengers	Concentrate on creating new bypasses and tangential connections within the city to reduce pressure on highly congested nodes and increase accessibility at stations with functional surplus	München Sendlinger Tor München Hohenzollernplatz
Suburban Places	Stations with proximity to larger cities Very good accessibility towards neighbouring centres Residential surplus	Improve local mix of jobs, housing and facilities	München-Lochhausen
Stations in Transition	Stations with the highest accessibility gains due to the second trunk line Residential surplus Location attractiveness expected to grow further	Prepare for future accessibility gains by providing space for dense, mixed-use new development, including residential	Weßling Eichenau
Rural Areas	Low functional density High functional deficit and residential surplus High new building potential	Despite high building potentials, refrain from residential densification. Enhancement of land use mix desirable but little demand. Consider relocation of stations towards settlement areas or merging where possible.	Otting-Weilheim Rohrbach (Oberbay.)
Boundary Places	High functional surplus Average mix of uses and development potentials Often overall low accessibility (e.g., stations at end of lines)	Focus on improving accessibility by creating new high-quality public transport/railway links with other Boundary Places	Füssen Bad Tölz
Traffic Hubs	Isolated interchange stations with bus links and car parks Often serve larger surrounding area or airport High accessibility	Settlement should grow towards the station if outside Establish a new sub-centre (shopping, leisure, workplaces, residential)	Hallbergmoos
Commercial Places	High residential deficit Low functional density High potential for densification and new buildings Often greenfield developments with large parking areas	Strengthen residential uses Increase density of functions, establish smaller businesses More compact parking solutions	Graben (Lechfeld) Gewerbepark

Table 6-3: *Characteristics, policy recommendations and examples for the clusters.*

6.6. Conclusion

In this paper, we have reviewed the debate on regional urbanisation, a new complexity and simultaneity of population and employment concentration and de-concentration and a blurring of urban and suburban spaces, in times of economic and demographic change. We have connected this debate with the effects of transport infrastructure extensions, using the "Second Trunk Line" ("Zweite Stammstrecke") express rail project in Munich as a case study.

With respect to recent commuter data, we confirmed the functionally, still relatively monocentric structure of the Munich Metropolitan Region (MMR) despite signs of polycentric development and de-concentration of economic activity in the immediate surroundings of Munich, essentially confirming previous literature on the case. This monocentricity is resembled by the settlement and transport structure and reinforced by the Second Trunk Line project. The Second Trunk Line doubles the existing east–west local train tunnel across the inner city and will allow express train services that skip most of the existing commuter belt around Munich. Instead of focusing on increasing accessibility for areas that are high-density but poorly served, it increases absolute accessibility for those central locations within the MMR that already exhibit high accessibility levels, which gives centrally located firms and shops an even greater locational advantage due to their relational proximity to customers and potential employees. At the same time, relative accessibility of several peripheral, low-density areas will drastically increase as well. Previous studies have already found a strong reactivity of land users in the MMR on (rail-based) public transport extensions, in the form of suburbanisation and metropolisation. Since the pressure on the housing market has only become greater, the second trunk line will likely lead to further polarisation and segregation of land uses and the suburbanisation of residential uses, on the one hand, and the agglomeration of commercial uses in the city centre, on the other. In an aggregate view, it will likely improve productivity in the region, leading to further metropolisation. Another, more tangential and polycentric alignment, as other metropolitan regions in the European context show, would have spread these effects more evenly, encouraging greater regionalisation of economic activity, if desired. Hence, the MMR presents a laboratory situation for other European metropolitan regions with regard to the effects of a heavily monocentric public transport alignment.

However, while new infrastructure in the long run means induced longer commutes and more traffic, settlement structures oriented on rail-based public transport are at least preferable to car-oriented structures in terms of emissions. Refraining from using the generated development potentials would mean an inefficient use of resources, and most inner-city building potentials have already been used. Development around stations should hence be dense and socially as well as functionally mixed, to reduce the necessity for commuting, but tailored to local capacities and restrictions. Such a selective and impact-oriented supply-based strategy, however, requires a common regional commitment and cooperation, which cannot yet be recognised.

Based on a cluster analysis of all 512 rail-based public transport stations in the region, we recommend policies tailored to the capacities and opportunities of seven groups of stations. The recommendations range from deliberate encouraging of sub-centre formation at transit hubs to relocations of stations in rural areas. The cluster analysis furthermore points to the importance of measures not only in the area of urban development but also the further improvement of the transport network, e.g., through gap closures and the creation of tangential connections on different spatial scales. While there are already elementary tangential public transport connections between most of the regional centres, high-performance tangential connections are largely missing in Munich on the city level and city-regional scale. This would also have moderating effects on the strong concentration of employment in Munich, which currently strains both housing markets and transport infrastructure. The categories, while tailored for the Munich MMR, might also be applicable in other metropolitan regions, based on their general characteristics.

Technically, we have proposed a multi-method approach, combining strategies from different strands of spatial sciences: commuter data analysis, accessibility modelling, node-place analysis and cluster-based policy recommendations. Particularly, we have proposed an extension to the node-place model by a perspective that more strongly takes into account a small-scale functional mix. This strengthens the perspective of traffic avoidance to the model that it otherwise mostly focused on efficiency of transit provision and land use allocation. In a further step, it would be useful to also look at areas that are currently still too far away from public transport stations but that would justify a connection based on their functional density. These are commonly not covered by the node-place model in its basic form. It is also important to consider that the node-place model is always relative to the station with the highest node and place values, which might not actually be "stressed" in absolute terms.

Gravitational accessibility studies often use only population as general measure of opportunities; this is also the case in this study. The use of accessibility of firms, shops or cultural amenities could however yield more precise measures regarding the locational advantages of stations for a range of users of space, and hence, it represents an avenue for the future specification of the results.

A major constraint of the results presented here is the fact that they consider only travel time to be decisive for location choices, not other characteristics of the transport mode, particularly the monetary efforts of commuting, which represent a strong spatial drag as well. Often, these are considered to be proportional to commuting time, but this is certainly too simplistic. More in-depth studies should take an integrated view of time and monetary costs of travel and consider relative price levels between different modes of transport. The current reform of the tariff structure in the Munich region would represent a good case to study the differential effects of tariff reductions and increases for single localities in the case study area.

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7. Conclusion

This chapter summarises the main results of the publications embedded in this dissertation, i.e. the previous chapters, and revisits the spatial impact diagram presented in the introduction to assess it on the background of the findings. It briefly sketches consequences for current and future plans of High-Speed Rail (HSR) infrastructure in Germany and beyond. Finally, it outlines aspects that require further research in the future.

7.1. Summary of findings

As described in the introduction, this dissertation is divided into three sections: quantification and mapping of accessibility dynamics, analysis of urban development associated with accessibility changes, and the development of policy recommendations. Chapters 2 and 3 were concerned with the question, where and how strong rail accessibility has changed in the last decades and will change in the next ten years, on a regional scale within Germany, without consideration of urban development changes. They formed an important foundation for the understanding of the following chapters 4 and 5, which were concerned with the built environment of the station and its surroundings. Finally, chapter 6 applied the combined methodology of the previous chapters to a metro-regional transport system with a greater focus on policy recommendations from a sustainable urban development perspective.

Chapters 2 and 3 introduced a monomodal regional rail accessibility model for Germany and surrounding countries, with 266 functional urban areas as spatial base units, which was applied using data for five points in time in 10-year intervals from 1990 to 2030. Both chapters used a potential accessibility measure based on an exponential decay function calibrated for business trips and a degree centrality measure for direct regional connections.

Chapter 2 looked at previous accessibility changes until today, while chapter 3 projected future accessibility changes based on the planned new rail lines contained in the current German Federal Transport Infrastructure Plan. The necessary timetable data had been assembled using web-scraping methods, which have made previously untapped sources available for research. The analyses generally confirmed previous studies – finding rail accessibility levels along the Rhine valley to be the highest throughout all phases. Regarding gravitational accessibility dynamics, the analyses found no evidence for growing disparities in Germany despite the discontinuation of intermediate long-distance trains and the construction of HSR infrastructure. Instead, there has been a balancing of accessibility levels throughout the study period, which was particularly strong between 1990 and 2000, slowing down afterwards. The 2020-2030 period is again projected to lead to a greater balancing of accessibility levels if all currently planned projects are realised. Nevertheless, rail accessibility has increased distinctly in the South and East of Germany, and less in the North and West. With regard to degree centrality, the studies found a reduction of direct change-free connections between regions in favour of a concentration of long-distance lines on major metropolitan hubs, which is expected to be reversed in the 2020-2030 period. The analyses found that the refurbishment of conventional rail lines and reopening of formerly dismantled cross-border lines in Eastern Germany after

1990 have largely overshadowed effects of HSR, particularly in the first decade after reunification, despite the fact that HSR has led to extraordinary accessibility improvements in some cases. HSR effects in Germany have furthermore transcended the classical urban-periphery dichotomy and are spatially more extensive, but also more discretionary. This is due to the interlinkage of HSR and conventional rail, the more dispersed settlement structure and piecemeal implementation of HSR compared to other European countries. Unlike in other countries, the most accessible region in Germany is not the capital city.

Chapter 4 analysed land use changes in the surroundings of HSR stations in Europe, using a database of 232 stations in 187 city-regions across eleven European countries. To assess the scale and type of land cover changes, CORINE land cover data was used. City-regions were categorised into seven types according to the locational and network-related characteristics of their rail connections. The chapter confirmed existing literature in three aspects: (1) station location strategies of European rail companies are changing towards more integrated, urban stations; (2) peripheral station locations are associated with industrial and commercial land cover changes and urban fringe, rather than exurban and inner-city stations which can be mostly associated with new urban development; (3) exurban stations far from any urban areas are not associated with urban development. Hence, chances for new urban development around HSR stations are highest for urban fringe locations; close to existing urban development, but with enough available building land; that are well integrated with local and regional public transport. Furthermore, the chapter found that those stations with the strongest land cover changes were located within one hour from major European metropoles (Reims-Pairs, Montabaur-Frankfurt and Cologne, Ciudad Real-Madrid). Together, these findings confirm the hypothetical relations of the impact sketch (Figure 1-9), particularly the hypothesis that a combination of local agglomeration and transport-related network externalities can support urban development.

The analysis has shown a simultaneous growth of land cover changes during the opening phase of the infrastructure and in the following 6-12 years, but not in the longer term after the station opening, casting doubt over the existence of long time lags. Foreshadowing effects of new infrastructure could not be determined. Instead, the temporal view highlights the strong impact of business cycles on the construction industry. In addition, somewhat surprisingly, the study could not detect an influence of the level of service and the architectural quality of a station on local urban development.

Chapter 5 focused on station buildings of new HSR stations asking whether accessibility and the quality of architecture and the commissioning of renowned architects are related. The results show that the strength of the relationship differs by country, pointing to a variation in importance attached to station architecture by the different (national) entities responsible for station planning. The analysis revealed several cases in which the importance and accessibility level of a station is disproportionate to the significance of the architect or the perceived quality of the station by users. Either such situations represent a missed opportunity to increase the attractiveness of the rail system or they hint at other motivations than the attractiveness of the station itself. The finding that redeveloped historical station buildings attract a higher recognition than most star architecture buildings furthermore shows the potential for working with the existing structures. Methodologically, the attempt to quantify 'star' status and recognition of buildings using Avery index and TripAdvisor scores has proven difficult, however. Pitfalls in the form of missing data, unclear intentions of user-generated data and questions of manipulability limit the validity and make it difficult to attribute effects clearly.

Chapter 6 presented another change of scale to the metro-regional level and it introduced a normative perspective of matching accessibility levels to local land use – based on the findings of the previous chapters – which has advantages from a sustainable urban development perspective. The chapter described the accessibility effects and ensuing development potentials from the currently planned "Second Trunk Line" ("Zweite Stammstrecke") express rail project in Munich as a case study. The analysis found the project to reinforce the existing monocentric urban and commuting structure in the region. Instead of focusing on increasing accessibility for areas that are high-density but poorly served, it increases absolute accessibility for those central locations within the Munich Metropolitan Region (MMR) that already exhibit high accessibility levels, which gives centrally located firms and shops an even greater locational advantage due to their relational proximity to customers and potential employees. At the same time, relative accessibility of several peripheral, low-density areas will drastically increase as well. Previous studies have already found a strong reactivity of land users in the MMR on (rail-based) public transport extensions in the form of suburbanisation and metropolisation. Since the pressure on the housing market has only become greater, the second trunk line will likely lead to further polarisation and segregation of land uses and the suburbanisation of residential uses, on the one hand, and the agglomeration of commercial uses in the city centre, on the other. In an aggregate view, it will likely improve productivity in the region, leading to further metropolisation. Another, more tangential and polycentric alignment, as other metropolitan regions in the European context show, would have spread these effects more evenly, encouraging greater regionalisation of economic activity, if desired. However, while new infrastructure in the long run means induced longer commutes and more traffic, settlement structures oriented on rail-based public transport are at least preferable to car-oriented structures in terms of emissions. Refraining from using the generated development potentials would mean an inefficient use of resources and most inner-city building potentials have already been used. Development around stations should hence be dense and socially as well as functionally mixed to reduce the necessity for commuting, but tailored to local capacities and restrictions. Such a selective and impact-oriented supply-based strategy, however, requires a common regional commitment and cooperation, which cannot yet be recognised. Based on a cluster analysis of all 512 rail-based public transport stations in the region, the chapter recommends policies tailored to the capacities and opportunities of seven groups of stations. The recommendations range from deliberately encouraging sub-centre formation at transit hubs to relocations of stations in rural areas.

7.2. Consequences for transport and urban planning practice

The results of this dissertation implicate certain recommendations for action for transport planning and urban development, both in a general and a specific way.

For urban planning, the dissertation highlights the importance of network-oriented thinking and the consideration of flows, rather than the previous, mostly static location-oriented approach to planning. It argues for a sustainable, transit-oriented development around rail stations and identifies substantial further potentials in the case of previous and future HSR projects. Particularly, it highlights the importance of considering both agglomeration and network economies in the planning of development zones around rail stations. At the same time, it confirms previous research in the sense that such development cannot be assumed as automatic, but requires careful planning and supporting conditions.

For transport planning, it presents a reinvigoration of the guidance that the parameters of large technical infrastructures, particularly their nodes of entry and scalar interconnection, should not be determined by technical engineering aspects alone. Instead, they must consider genuine local requirements of urban design, local and regional planning, as well as pre-existing networks to improve their usability for less densely populated regions apart from the main metropoles. It argues for a supply-oriented planning and implementation of transport infrastructure, including HSR infrastructure that does not merely improve bottlenecks incrementally, but follows an integrated urban and transport planning vision which ensures adequate and proportional accessibility of all regions, including peripheral ones, to the long-distance rail network. Such a supply-oriented perspective, which has been successfully implemented previously in a range of European countries, such as the Netherlands, Switzerland, and in the recent Federal Transport Infrastructure Plan 2030, is highly supported and could present further opportunities applied on a European scale.

The consequences for HSR planning in Germany can be described in more detail using an example of an already constructed HSR line, the Cologne-Frankfurt line, and two examples of currently planned HSR lines: The Erfurt-Fulda line and the hinterland connection of the Fehmarn Belt Fixed Link.

The cases of Montabaur and Limburg Süd are highly instructive for the interrelations between HSR and urban development. Both stations are located within a distance of less than 10 minutes by HSR, about mid-way on the line between **Cologne and Frankfurt**, opened in 2002, and can hence be compared well. While there is considerable development in Montabaur, the large commercial area zoned next to Limburg Süd station has remained almost completely unutilised so far. The main difference between the stations is their urban and transport embeddedness: while Montabaur station is within walking distance of the city centre and all local and regional train and bus connections are concentrated at the new node, Limburg Süd is in a greenfield location outside of the city proper with only sporadic bus connections to the city centre. The results of this dissertation suggest that this missing embeddedness and interconnection is a main reason behind the failure of the business park in Limburg. This is particularly unfortunate given the background that alternative station locations for the HSR stop in Limburg had been discussed during the planning phase, especially one in the district of Staffel to the north of Limburg close to an existing commercial area, as well as an alternative location in-between the twin-cities of Limburg and Diez (Blind 1992: 1063). Both locations would have been highly preferable in terms of urban and public transport integration, but had been rejected due to the more convenient construction site at Limburg Süd.

Plans to upgrade and partially complement the existing conventional line between **Erfurt and Fulda** for HSR are far advanced. As a part of this project, which is intended to reduce travel times between Berlin and Frankfurt to less than three hours, a new stretch of HSR line for 250 km/h is to be constructed between Fulda and the town of Wildeck near Eisenach, bypassing Bad Hersfeld, which is currently served by ICE trains using the conventional line. Bad Hersfeld, a town of about 30.000 inhabitants, is centrally located within Germany and the seat of several important companies, among them the German headquarters of online retailer Amazon. The Federal Transport Infrastructure Plan and its derivative "Deutschland-Takt" package continue to contain long distance services in Bad Hersfeld. One option would be to continue to route one train pair every two hours via the existing line despite the availability of the new, faster HSR line. Another option would be to construct a branch line connecting the new HSR line with the existing conventional line either in one or both directions. In both of these cases, the existing station of Bad Hersfeld would continue to be served by long distance services. On the background of the findings of this dissertation, this would represent the preferred option, also in terms of urban development, as the existing station is well integrated with the urban fabric as well as the existing local and regional public transport. At the same time, an analysis of aerial photographs suggests that (re)development potentials around the station location still exist.

The third option would be to construct an entirely new station on the HSR line that bypasses Bad Hersfeld. Several potential alignments of the new line are discussed that bypass Bad Hersfeld entirely (DB Netz AG 2020a). A strategy comprising the bundling of motorways and HSR infrastructure – which reduces consumption and fragmentation of landscape and has been successfully applied in case of the Cologne-Frankfurt and Ingolstadt-Nuremberg lines – would be possible along the existing A4 motorway, but is not among the remaining variants in discussion. This is also regrettable from an urban development perspective, as a location next to the A4 on its intersection with the conventional rail line, located next to a commercial area, would have represented a second-best choice for a HSR stop in Bad Hersfeld. This location would be sufficiently close to the urban core of Bad Hersfeld (1.5 km) and exhibits more available building land than the existing station location. At the same time, it is very close to the Amazon headquarters and other major local firms, which represent potential sources of agglomeration economies. However, a route along the A4 would also be very close to residential areas near Bad Hersfeld, which would require more expensive tunnelling and noise protection measures.

Should the options of connecting the existing station to the HSR line not be realised, it is hence likely that an entirely new "greenfield" station will be constructed near Bad Hersfeld on a location that might be convenient from a transport engineering perspective, but not integrated with the urban fabric or the existing conventional line. This would not only lead to a greater dominance of individual transport as access mode, but would also mean the forfeiting of opportunity in terms of urban development.

The last current project that demonstrates the policy recommendations developed in this dissertation is the hinterland connection of the **Fehmarn Belt Fixed Link**. The Fixed Link is a tunnel that is going to replace the already discontinued train ferry between the German town of Puttgarden on Fehmarn Island and the Danish town of Rødby. It is part of the wider Hamburg-København relation and is planned to enter into operation in 2029. The Fixed Link requires the upgrading of the outdated current, single-track non-electrified railway line between the German end of the tunnel in Puttgarden on the one hand, and the city of Lübeck on the other, which currently only allows top speeds of around 100 km/h for most stretches. Planning of this line is more advanced than the Fulda-Erfurt line and a final line variant has already been selected (DB Netz AG 2020b). To reduce overall travel times and reduce noise immission it bypasses most of the small and medium-sized towns between Lübeck and Puttgarden, such as Oldenburg (Holstein), Timmendorfer Strand, and Scharbeutz at a greater distance, which are currently served by centrally located stations along the existing line.

Controversially, the existing line is to be entirely decommissioned after the new line enters in operation. This is particularly surprising considering that many of towns along the line are popular destinations for day trips from Hamburg and for beach holidays from Northern Germany. Replacement stations are to be constructed along the new alignment, on open space at distances of about 2 km distance from the existing urban area and no longer in walking distance to the seaside, which is likely to increase the share of visitors to these towns arriving by car. Based on the findings of chapter 4 this approach is likely to diminish the existing complementary interlocking agglomeration and network economies at the entry nodes to the rail system. Instead, their remote location means that they will be inhospitable for customers and not be able to attract any meaningful urban development. Moreover, existing urban cores will be deprived of an important catalyst of urban development. A solution could be to separate different types of rail traffic, keeping the existing line in place for regional trains and using the new line for HSR and freight trains only. The additional costs of maintaining two parallel lines can potentially be offset by the urban development advantages and the reduced scope of the new line (no need to construct new stations).

7.3. Avenues for further research

This dissertation could only touch upon some of the relations detailed in the spatial impact diagram, and several impact relations remain to be investigated further. In addition, major research endeavours often reveal interesting side issues and niches that cannot be covered adequately without deviating too far from the original research goal, particularly in a publication-based dissertation. This final section briefly summarises issues in the realm of (High-Speed) Rail infrastructure and spatial development that could be profitable for further research.

Methodologically, quantitative-generalised approaches like those dominantly used in this dissertation should be complemented by further **bottom-up, case study based analyses** of local circumstances, such as the analysis of land use plans and interviews with local decision-makers, to verify and contextualise the findings of top-down analyses. Only such a triangulation of methods can ultimately ensure the firm establishment of causal inferences.

While chapters of this dissertation have used population and land uses as dependent variables, further analyses could extend the analyses presented here to disaggregated local data, particularly **locational data of knowledge-intensive firms** as well as **land prices and office rents**, to identify relationships between HSR-induced accessibility changes and business development.

Regarding the content, this study has mostly focused on long-distance HSR stations; however, particularly in Germany, there has been a trend towards the construction of dedicated "**Regional HSR**" stops and the commissioning of regional train services even on high-speed rail lines by the federal states. Specifically, the federal states have subsidised Deutsche Bahn for upgrading siding places – originally only meant to allow faster trains to overtake slower ones – to proper train stops on several lines. The location of such sidings is purely determined by technical parameters (spacing of 20 km, on level ground) not by proximity to settlements. Nevertheless, as a result the stations of "Allersberg (Rothsee)", "Kinding (Altmühltal)" and "Merklingen – Schwäbische Alb" have been constructed. They are now served exclusively by slower "Regional HSR" trains, subsidised by the States of Bavaria and Baden-Württemberg, which can be used with cheaper regional train tickets. The state of Thuringia, on the other hand, has renounced the option to construct such a stop on sidings near Ilmenau on cost-benefit grounds. It would be an interesting endeavour to study economic and social developments around such "Regional HSR" stations in more detail since they have been justified explicitly with regional policy aims, particularly since regional train services are more adjusted to the needs of commuters.

The greater **integration of rail and air services** has been another recent trend and a dedicated political goal of the European Union. Due to customer preferences, monomodal rail accessibility analyses lose explanatory power for large distances that can be covered faster by air transport, or a combination of air and rail. Hence, accessibility models like the one presented in this dissertation should account for multi- and intermodal forms of transport if they are applied on an international scale. Such models can then be used to identify weaknesses in the integration of modes, particularly hub airports that are weakly connected to the rail network of the greater region they serve. Despite the critically discussed environmental balance of air transport and the current pandemic, air transport will certainly remain an important backbone of the global passenger transport network particularly if Co2-neutral fuels become widely used. The integration of rail and air transport can help to reduce land consumption for airport expansions and free up slots at congested airports.

Quality and quantity of data available to researchers continues to increase and computing tools become more powerful. The raw data used for the analyses in this dissertation has been aggregated and cleaned on several occasions to allow intertemporal comparisons. However, **spatially and temporally more detailed analyses** would be possible with the investment of more time and resources. For example, the historical timetable data could be converted into

GTFS format, which is now widespread also in transport research, to allow a variety of more detailed accessibility measures to be developed. Following a time-geographical approach (Hägerstrand 1970), the identification of relations within certain critical time thresholds (e.g. day business travel) within Germany akin to the analyses of Moyano, Rivas and Coronado (2019) for Spain, would be highly interesting. In addition, there are further more insightful ways to visualise the accessibility "landscapes" generated by HSR (L'Hostis 1996) which could be applied to the data generated in this project.

Furthermore, research on effects of transport infrastructure often concentrates on travel time savings alone and does not consider monetary travel costs – so did this dissertation. This methodological choice is founded on the rationale that monetary costs of travel are either (a) proportional to travel time and can hence be considered as 'subsumed' therein, (b) are overwhelmingly outweighed by the advantages of shorter travel times, particularly for high-income individuals, and can therefore be neglected, or (c) are only of minor importance in the case of commuters, since they can be deduced from income taxes, or are even entirely irrelevant in the case of 'flat-rate' travel passes such as the German "Bahncard 100". However, these conditions do not necessarily hold in all cases: new pricing strategies of rail companies follow the demand-oriented pricing models of airlines and are largely independent of distance or travel time and flat-rate passes are unknown or very expensive in many countries with HSR, such as France or Japan. **Price-sensitive HSR accessibility analyses** would hence present another research opportunity for the future.

Finally, this research has primarily looked at situations of increasing accessibility. The main aim was to localise such increases, identify associated spatial developments, and suggest planning strategies to deal with such situations. However, the regional accessibility analyses over time for Germany (chapters 2 and 3) also identified a few **cases of declining accessibility** particularly with respect to direct connections. Several mid-sized cities, such as Jena, Magdeburg, and Potsdam, as well as smaller towns, such as Naumburg, Saalfeld, and Bebra have significantly lost direct long-distance train connections to other regions since 1990, mostly in the course of HSR introduction on parallel lines, even though their gravitational accessibility might have remained stable. In addition, the main access point to the long-distance rail network has been relocated in several cities in the course of HSR introduction, for example in Kassel, where the former main station is now only served by regional trains. Actually, such situations have occurred more often in other European countries particularly France and Spain. Here, theoretically, the reverse of the impacts charted out in the spatial impact diagram should apply and it would be worthwhile to conduct a separate study focussing on the regional and especially the local changes of land uses around such stations.

7.4. References

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