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Vorwort zur Schriftenreihe

Verkehrsaktivitäten stehen in vielfältigen Wechselwirkungen mit ihrem wirtschaftlichen, ökologischen und sozialen Umfeld. Der Lehrstuhl für Verkehrsökologie beschäftigt sich in Forschung und Lehre mit diesen Wechselwirkungen, denn nur eine zusammenfügende Betrachtung kann sinnvolle und tragfähige Lösungen ergeben. Übergeordnetes Ziel aller Arbeiten des Lehrstuhls ist es, entsprechend der offiziellen Widmung „zur Verringerung der Umweltbelastungen aus dem Verkehr beizutragen“. Schwerpunkte sind dabei Arbeiten zur Umsetzung einer nachhaltigeren Verkehrsentwicklung, die in folgenden Themenfeldern konkretisiert werden:

a) Nachhaltige Verkehrsentwicklung: Auswirkungen, Verfahren, Konsequenzen
b) Klimaschutz, Energie und CO_2 im Verkehr
c) Luftreinhaltung & Lärm, Emissionsfaktoren und reale Fahrmuster
d) Externe Kosten und Nutzen des Verkehrs, Kostenwahrheit und Internalisierung
e) Rad- und Fußverkehr
f) Umweltbildung, Monitoring und Evaluation
g) Soziale Exklusion und Umweltgerechtigkeit im Verkehrsbereich

Die Ergebnisse der dazu durchgeführten Untersuchungen sowie ausgewählter studentischer Arbeiten sollen im Rahmen dieser „Verkehrsökologischen Schriftenreihe“ einer breiteren Öffentlichkeit zugänglich gemacht werden. Damit möchten wir einerseits die fachliche Diskussion zu Problemstellungen einer nachhaltigen Mobilitätsentwicklung und anderseits den offenen Zugang zu Wissen und Informationen unterstützen.

Die in dieser Veröffentlichung vorgestellte Studienarbeit von Herrn Leonard Arning führt eine Analyse der Wirkungen des schienengebundenen Hochgeschwindigkeitsverkehrs auf die Erschließung und Umweltwirkungen durch. Dafür wertet der Autor eine umfangreiche Auswahl nationaler und internationaler Forschungsarbeiten aus.

Der Autor kommt zu dem Schluss, dass sich schienengebundener Hochgeschwindigkeitsverkehr nicht zwangsläufig positiv auf die Umwelt und die Erreichbarkeit auswirkt. Dies ist abhängig von der Topographie und Siedlungsstruktur, durch die die Trasse führt. Die bessere Erschließung kann kurzfristig zu einer größeren räumlichen Gerechtigkeit beitragen. Langfristig kann sich dieser Effekt durch eine potenziell regionale Konzentration von Einrichtungen und Dienstleistungen allerdings wieder aufheben. Entscheidend für die Nachhaltigkeit sind hohe Auslastungen, wenige Kunstbauten und ein Strom aus regenerativen Energiequellen. Die Größe der Verkehrsverlagerung und der induzierten Verkehrsnachfrage hängen stark von den räumlichen Gegebenheiten ab. Der Ausbau des Hochgeschwindigkeitsverkehrs reduziere nach Meinung des Autors nur dann die Emissionen des Luftverkehrs, wenn weitere politische Maßnahmen getroffen würden.

Der besondere Wert der Arbeit liegt in der umfangreichen und systematischen Zusammenfassung des aktuellen Forschungsstands.

Wir danken Herrn Arning sehr herzlich für die sehr engagierte und systematische Bearbeitung der Fragestellung. Sie ist ein wichtiger Beitrag in der fortlaufenden Weiterentwicklung des Hochgeschwindigkeitsnetzes.

Dresden, 29.07.2024 Udo J. Becker, Julia Gerlach

Executive Summary

High-speed rail (HSR) is commonly assumed to cause fewer specific greenhouse gas emissions than alternative transportation systems such as aviation or road transport. Therefore, HSR projects leading to a mode shift from these modes to HSR are supposed to be beneficial to the environment by mitigating climate change. HSR can also provide new and speedy connections between peripheral regions and economic centers. It is thought that by providing peripheral regions with easier access to goods and service only available in large urban centers, HSR improves the economic competitiveness of these regions as well as spatial equity.

To investigate the current state of research regarding these issues, I first systematize accessibility and environmental impacts from transportation in general and HSR specifically. I then carry out a systematic literature review across three scientific databases, using two search strings, resulting in a literature corpus of 79 unique sources. Results from these sources are analyzed and summarized in five research fields: spatial equity, carbon intensity, mode shift to HSR, induced HSR demand and complementary effects.

I find that HSR improves accessibility of all regions, even those that have no direct access to HSR service. However, the impact on economic growth and spatial equity can be negative or positive depending on case characteristics. Carbon intensity of HSR is highly variable, in some cases even exceeding that of air transport. I find extreme cases of 10 and 283 gCO2/pkm. High ridership, a low share of tunnel and bridge sections, as well as a green electricity mix are crucial to ensure that HSR exhibits lower specific carbon emissions than alternative modes and has the potential to reduce overall GHG emissions. Mode shift and induced demand are also highly dependent on the individual project's case, with induced demand typically being between 10 and 20 % of the total HSR demand. Concrete values of complementary effects, which is the additional demand in modes competing with HSR, are the least extensively studied. Especially air transport appears not only to compete with HSR, but also to exhibit several complementary relationships such as price competition and an increased attractiveness of long-haul flights. I conclude that, assuming no additional policy measures being taken, expanding HSR does not lead to a reduction of overall greenhouse gas emissions from air transport. The environmental impact of a HSR project can be estimated through a vigorous project appraisal process only.

Important policy implications include the enhancement of appraisal processes as well as the overall need for deploying HSR projects in push-and-pull packages with other, supply-restricting policies. Future research should direct more attention towards HSR and airfares. I propose study designs for a national flight emission study and including passengers' destination choice in existing research approaches. I also suggest using the results of this student research paper to carry out a Monte Carlo simulation on HSR projects' recuperation periods.

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LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ASE	Academic Search Elite
AVE	Alta Velocidad Española
CAHSR	California High-Speed Rail
CO	carbon monoxide
CO2	carbon dioxide
CO2eq	carbon dioxide equivalent
CR	conventional rail
EU	European Union
GDP	gross domestic product
GDPPC	gross domestic product per capita
GHG	greenhouse gases
GIS	geographic information system
GWP	global warming potential
HC	hydrocarbons
HS2	High-Speed 2
HSR	high-speed rail
ICE	Intercity Express
LAP	local air pollution
LCA	life-cycle assessment
LCC	low-cost carrier
LGV	lignes à grande vitesse
NOx	nitrogen oxide
PM	partuculate matter
Renfe	Red Nacional de los Ferrocarriles Española
RFF	Réseau ferré de France
RFI	radiative-forcing-index
RP	revealed preference
SARS	severe acute respiratory syndrome
SNCF	Société nationale des chemins de fer français
SO2	sulfur dioxide
SOx	sulfur oxide
SP	stated preference
SpREI	Spatial Railway Equity Index
TRID	Transport Research International Documentation
UIC	Union Internationale des Chemins de fer
UVPG	Gesetz über die Umweltverträglichkeitsprüfung
WOS	Web of Science

1 INTRODUCTION

HSR is widely regarded as an integral part of the solution to combat climate change. Lower environmental burdens compared to other modes combined with a mode shift are supposed to result in a reduction of overall emissions and a mitigation of global warming. At the same time, HSR projects presumably improve accessibility and economic competitiveness. It therefore seems to be a tool to break up the often-found conflict between environmental protection on one hand and increasing mobility and economic growth on the other. However, at first glance scientific findings from the literature are contradictory regarding the overall environmental impact of HSR. This prompted me to investigate this question in the form of a student research paper, which I hereby present.

Following this introduction, the second chapter provides definitions of central terms used throughout this paper. In addition, environmental and accessibility impacts of transportation in general and HSR specifically are researched and systematized. I also describe their causal relationships with each other and the relevance of each to the topic.

This research paper is literature-based because the current state of research regarding the overall environmental impact of HSR is in fact unclear, as is what types of research even exist. For that reason, emphasis has also been placed on providing an overview over methods used in existing research and developing approaches for future studies. I decide to carry out a systematic literature review, because it allows comparing findings and methods of sources from a representative body of research. I construct two search strings based on the results from the second chapter and query three scientific databases, resulting in a literature corpus encompassing 79 unique sources. Details about these procedures are presented in the third chapter.

The fourth chapter constitutes the main part of this student research paper. Here, I present the findings from the analyzed literature organized in five research fields. These research fields are developed based on the systematization of environmental and accessibility impacts from the second chapter as well as the contents of the analyzed sources. The first research field deals with issues regarding the spatial and economic impact of HSR on peripheral regions. The second to fifth research fields each deal with one property or relationship of HSR that determines its overall environmental impact. Namely, the five research fields are:

1. Spatial equity
2. Carbon intensity
3. Mode shift towards HSR
4. Induced HSR demand
5. Complementary effects

In chapter five, I draw conclusions regarding the overall environmental and accessibility impact of HSR. The overarching question is, under what circumstances the construction and operation of a new HSR line is beneficial to spatial equity and the environment. Policy implications as well as methodological limitations of existing research and future research needs are pointed out. Lastly, I suggest study designs for future research.

2 DEFINITION AND SYSTEMATIZATION

Before systematically reviewing the literature, the terms used in the research assignment have to be defined. Based on these definitions and a preliminary literature research I develop two systematizations for the purpose of this paper, one for environmental and one for accessibility impacts. The causal relationships between the different environmental and accessibility impacts as well as their relevance to the research topic are explained. The systematic literature review in chapter 3 then builds upon these systematizations.

2.1 HIGH-SPEED RAIL

High-speed rail (HSR) is a term generally used to describe railway technologies (i.e. rolling stock, infrastructure or patterns of operation) that operate at speeds higher than conventional railways (CR) (Banar & Özdemir, 2015:88; UIC, 2020). A precise delimitation of CR and HSR can be challenging. In contexts where both types of railways use common infrastructure, there can be a smooth transition in operation speed from regional rail over high-speed trains using existing or upgraded infrastructure to high-speed trains running at full speed on dedicated tracks (Perl & Goetz, 2015:3; Sun et al., 2017:4). In other regions, the absence of HSR in a narrow sense can enable project sponsors to use the term to brand railway projects that are faster than existing services, but that would not meet HSR-criteria applied in other countries (Brightline Trains Florida LLC, 2020).

The United States Code contains contradicting definitions of HSR. For example, it states that

> “(2) the term "high-speed rail" means all forms of nonhighway ground transportation that run on rails or electromagnetic guideways providing transportation service which is- (A) reasonably expected to reach sustained speeds of more than 125 miles per hour; […]” (49 U.S.C § 26105).

Contrary to that, in a different context it states that

> “(4) […] The term "high-speed rail" means intercity passenger rail service that is reasonably expected to reach speeds of at least 110 miles per hour” (49 U.S.C. § 26106)

, thus demonstrating that the term HSR is not uniformly defined in United States law.

For the purpose of this paper, I adopt the definition of the Union internationale des chemins de fer (UIC). The European Commission (2010:4) and many other reviewed sources also apply this definition. According to the UIC, high-speed rail denotes “a whole, integrated system”, encompassing “infrastructure […], rolling stock […], telecommunications, operating conditions and

equipment, etc." (UIC, 2020). These different components must enable a speed of at least 250 km/h on newly constructed lines or at least 200 km/h on (usually upgraded) existing lines (ibid.).

2.2 IMPACT

In this chapter, I briefly consider the meaning of the term "impact" in the context of environmental and accessibility impacts. An online dictionary defines impact simply as "a powerful effect that something, especially something new, has on a situation or person" (Cambridge University Press, 2020). In economic and transportation literature, the term is used more precisely to describe "any consequence of the [transportation] service production and consumption process that falls outside producer and consumer themselves" (Catalano et al., 2019:11). For the scope of this research paper I therefore consider "impact" to be synonymous with external effects or external costs (not considering internalizations measures).

Impacts can be of direct or indirect nature. Direct impacts are changes in traffic volume or mode choice, while indirect impacts include secondary effects such as on the environment, economy or society (Department for Transport, 2019:6; X. Chen, 2015:348). I explorer these causal relationships in chapters 2.3 to 2.5.

2.3 SYSTEMATIZATION OF ACCESSIBILITY IMPACTS

This paper deals with the spatial dimension of accessibility, which is a central concept of transportation planning. While there are many different such accessibility measures, they generally describe the potential of activities and the ease of accessing them from a given point in space (Geurs et al., 2012:1,22,264; X. Chen, 2015:349). Using GIS platforms and other software solutions, more complex and disaggregate methods of calculation are developed and used, such as assessing accessibility on an individual instead of zonal level, for certain activities or for different time slices (Geurs et al., 2012:1f.). Accessibility for a given point is calculated based on the cost of reaching every other place, weighted by the potential of activity at those other places. This relationship is expressed mathematically as

Equation 1: General equation for accessibility

$$Acc_i = \sum_{j=1}^{N} D_j * f(\beta, c_{ij})$$

, "where Acc_i defines the accessibility of node or zone i; D_j is a measure (or weight) of opportunities and activities in j; and $f(\beta, c_{ij})$ is the impedance function from i to j, with β its cost-sensitivity

parameter" (Geurs et al., 2012:22). c_{ij} denotes travel costs between origin and destination, such as travel time, fares or number of transfers.

A wide range of variables such as jobs, population, GDP, or combinations of such structure sizes comes to mind for D_j, depending on what the respective accessibility analysis' focus is (Geurs et al., 2012:23). Like c_{ij}, D_j can also be transformed using logarithmic or power decay functions, such as when modeling modal market shares (Cascetta et al., 2020:417) or calculating spatial equity indices (Cavallaro et al., 2020:332). D_j can also be used as an untransformed weighting variable however. The impedance or decay function of travel costs $f(\beta, c_{ij})$ can take different forms, and comparison of the resulting accessibility measures can reveal the topology of the network (Geurs et al., 2012:23,26f.). To provide some examples, the five decay functions used in the accessibility analysis of the German commuting network for 2003 and 2007 as quoted in Geurs et al. (2012:24) are:

Equation 2: Exponential decay function

$$f(c_{ij}) = e^{-\beta_1 * c_{ij}}$$

Equation 3: Exponential-normal decay function

$$f(c_{ij}) = e^{-\beta_2 * c_{ij}^2}$$

Equation 4: Exponential-square-root decay function

$$f(c_{ij}) = e^{-\beta_3 * \sqrt{c_{ij}}}$$

Equation 5: Log-normal decay function

$$f(c_{ij}) = e^{-\beta_4 * \log(c_{ij})^2}$$

Equation 6: Power decay function

$$f(c_{ij}) = c_{ij}^{-\beta_5}$$

The power decay function is particularly suitable for models involving several large agglomerations, metropolitan areas and long distances, since it shows a higher tail than exponential decay functions (Geurs et al., 2012:23). This relates to the network characteristics of HSR, which is predominantly used for inter-urban travel.

The interpretation of absolute values of accessibility measures can be problematic. Accessibility measures often yield high numerical values, but do not allow for simple comparisons between different accessibility analyses and their units do not represent common concepts such as travel time or costs. It is also worth pointing out that the German terms “Erreichbarkeit” and “Lagegunst” both denote different subsets of accessibility measures. While Lagegunst is used for accessibility measures that transform travel costs using an impedance function, “Erreichbarkeit” denotes accessibility measures based only on either weighted or unweighted travel costs (i.e. using an impedance function of $f(\beta, c_{ij}) = c_{ij}$). In transportation sciences, the term “accessibility” can also be used to describe measures other than those explained in this subchapter. For example, it can also describe the ease of physical access onto a public transport vehicle for a mobility-impaired person or the accessibility of information about transport services (Department for Transport, 2020a:32). Other sources that look at the spatial dimension of accessibility do not include weighting and decay functions in their accessibility analyses. For example, the Department for Transport (2020b:50) recommends strategic accessibility analyses where travel time to the nearest amenity in question (such as a hospital) is calculated on the level of households and the change of the number of households in each travel time value range due to a project is interpreted as the project’s accessibility impact. In this research paper, I focus on accessibility measures according to the definition laid out in the first part of this subchapter.

Improving accessibility is often discussed as a driver or prerequisite of other desired spatial developments, such as job or economic growth (X. Chen, 2015:297). Accessibility is also a determinant of trip frequency and mode choice (Yao & Morikawa, 2005:370,379). In this paper, I therefore look at accessibility from the following two perspectives:

1. Improving accessibility in less accessible regions is thought of as one way to contribute to the political objective of equity of living conditions. While the aforementioned secondary effects of improved accessibility such as economic growth also contribute to this aim, ensuring access to periodic and specific goods, services and infrastructure from every region in practice poses a policy guideline in its own right (Ragnitz & Thum, 2019). Examples for such specific demands that cannot be provided in every region but need to be accessible within reasonable travel costs to ensure equitable living conditions include airports, cultural institutions, specific goods or specialized business services. Introduction of HSR has the potential to improve the access of peripheral regions to large urban centers and their diversified range of such goods and services. At the same time, withdrawal of long-distance rail services on legacy lines might reduce accessibility in other places.
2. Improving accessibility impacts travel behavior in several ways. If one calculates accessibility as a measure of generalized travel costs (i.e. c_{ij} consisting of not only travel time but also monetary costs, comfort etc.) it captures the attractiveness of the respective mode in a given place. Improved accessibility also leads to an increase in trip frequency (Yao & Morikawa, 2005:370,379). Potential effects of HSR introduction therefore include a

mode shift from alternative modes to HSR, but also additional journeys that would not have taken place otherwise. During the preliminary research, I identify three major and distinct impacts from changes in HSR accessibility:

a. Mode shift from alternative modes to HSR due to competition (Baron et al., 2011; Zhe Chen et al., 2019)
b. New HSR trips that would not have taken place otherwise (induced demand[1]) (Baron et al., 2011; Kasraian et al., 2016)
c. New trips in competing modes that would not have taken place otherwise (complementary effects[2]) (Albalate et al., 2015; Clewlow et al., 2012; D'Alfonso et al., 2016; F. Zhang et al., 2018)

All three accessibility impacts are relevant to the environmental impacts of HSR. Many studies assessing environmental impacts of HSR that I review in preparation of the systematic literature review include mode shift and induced demand. Complementary effects between HSR and other modes have not been studied as extensively (Albalate et al., 2015:1).

I examine the impact of HSR introduction on the equity of living conditions in peripheral regions in the first section of this paper's main part (research field 1: spatial equity). The three accessibility impacts mode shift, induced demand and complementary effects and their role in quantifying the environmental impacts of HSR are dealt with in research fields 3, 4 and 5 respectively.

2.4 SYSTEMATIZATION OF ENVIRONMENTAL IMPACTS

In context of the research assignment included in the beginning of this paper, the term "environmental impacts" aims at changes in environmental damage resulting from transportation related activities. However, the term "environment" can encompass many different components, the scope of which varies across the literature.

For example, the Information Resources Management Association (2015:32) names the environment's components as "soil, water, air and consequently all living species". Since humans are a living species, their health and wellbeing is also included. Secondary aspects of human life such as perception of the landscape or economic activity do not fall under this definition. Ionescu's (2016) assessment of environmental impacts of transportation is centered on GHG emissions (ibid.:xv,83,135), with only one chapter also naming other ecological factors such as roadkill, reduced dispersal capacity and impediments to gene flow, spread of invasive species and

[1] Including primary and secondary induced demand

[2] Some complementary effects can be viewed as demand induced by HSR in competing modes. For the sake of clarity, I restrict the use of the term "induced demand" to cases where demand is induced in the same mode that experiences an original expansion of supply.

landscape fragmentation (ibid.:106), all related to matters of biodiversity. D'Alfonso et al. (2016:264) regard local air pollution (LAP), climate change and noise pollution. The European Environment Agency (2015) assesses the four environmental pressures it regards as the most important ones across the EU-28. They are GHG emissions, air pollutants (NOx, particulate matter and SOx), noise pollution and biodiversity pressures (ibid.:27). Catalano et al. (2019) carry out a meta-study of current research on efficiency, effectiveness and impacts assessment in the rail transport sector. In doing so, the authors systematize the environmental impacts assessed in the literature into eleven factors. They are:

- air pollution
- climate change
- material use
- energy consumption
- noise and vibration
- water waste and pollution
- soil pollution
- nature and landscape
- biodiversity and wildlife
- land use
- up- and downstream processes (ibid.:12).

Some of these factors describe subsequent elements in the same chain of effects. For example, energy consumption triggers GHG emissions, which in turn cause an acceleration of climate change. This distinction is useful in the context of analyzing different research approaches but less so when it comes to assessing the environmental impact of a transportation system overall, where one should avoid counting multiple elements from the same causal chain.

Lastly, I look at the legal situation in the EU. Legislation in EU-member states has to conform to the Directive 2001/92/EU on the assessment of the effects of certain public and private projects on the environment. The directive explicitly names environmental factors that have to be considered in such assessments. They are:

> "(a) human beings, fauna and flora;
>
> (b) soil, water, air, climate and the landscape;
>
> (c) material assets and the cultural heritage;
>
> (d) the interaction between the factors referred to in points (a), (b) and (c)" (Directive 2001/92/EU, Art. 3).

While national legislation has taken different approaches for implementing the directive, this systematization of environmental factors is found there as well. For example, the German law on

environmental impact assessment (UVPG) describes the very same factors as so-called objects of protection (Schutzgüter, UVPG §2). Because Directive 2001/92/EU poses a consistent legal framework for environmental assessment of infrastructure projects in the European Union and it includes both direct and indirect effects, it serves as another reference point for types of environmental impacts of such projects.

For this paper, I exclude some factors mentioned in the sources above for a variety of reasons. Aggregate measures such as material use, energy consumption and up- and downstream measures are excluded, because they include more than one of the factors mentioned above. For example, energy consumption causes both LAP and GHG emissions and is therefore not considered being an independent environmental factor. Cultural heritage, material assets and landscape (concerning its reception by humans, utility for wildlife is included under biodiversity) is excluded because these factors are centered on economic or cultural interests instead of ecological significance. The impact of transportation projects on these factors is also highly dependent on the individual case and not suited for the general comparison of transportation systems.

The cited sources demonstrate that environmental impacts can be assessed on many different factors. There is widespread agreement (at least five out of the six sources mentioned above) on including at least the following clusters of factors:

- Climate (GHG emissions or only CO2 emissions)
- LAP
- Noise
- Biodiversity (including flora, fauna and habitat fragmentation)

To cover all possibly relevant environmental impacts of HSR in chapter 2.5, I expand this list to include six factors:

- Biodiversity
- Climate
- LAP
- Noise
- Soil
- Water

An aggregation of those factors could take place according to several different, equally justifiable approaches. For example, one can group them by the medium by which the impacts are transmitted (air, water…), by the societal objective which is harmed (human health, biodiversity…), or by their causal relationship. Some sources, such as the Directive 2001/92/EU, combine these approaches. For the systematization in this paper, I do not group the environmental factors assessed here. This is because of their small number and since the reviewed literature uses incompatible approaches.

2.5 CAUSAL CHAINS AND RELEVANCE

Transport related activities affect the environment via complex and interlinked causal chains. From the immediate effect of a transport related activity (GHG emitted by vehicles driving on a motorway), via chains of reactions (GHG causing global climate change), to the societal objective which is harmed (human suffering through rising sea levels, food shortages etc.), there are many different stages at which one can measure such impacts. In this chapter, I lay out briefly how HSR affects the six environmental factors from chapter 2.4 and decide which ones to include in the systematic literature review.

Biodiversity describes the variety of species inhabiting an area, both in terms of number of species and the genetic variance among their members (United Nations, 1992:3). While transportation infrastructure and operation affect biodiversity in several ways, such as by climate change (Maibach et al., 2008:72), land consumption or construction work (D'Alfonso et al., 2016:264), the reviewed literature generally focuses on assessing local impacts resulting from habitat fragmentation. Focusing on habitat fragmentation, biodiversity impacts of HSR are highly dependent on route alignment, elevation of the track above ground, frequency of trains and the level of biodiversity present. As a result, biodiversity impacts vary greatly from project to project and cannot easily be compared at the level of transportation systems. Biodiversity impacts of HSR lines depend on traffic volume to a smaller degree than on the built infrastructure. The magnitude of mode shift or change in travel demand is therefore less relevant for HSR's impact on biodiversity than characteristics of the built infrastructure.

Climate change impacts due to transportation mainly result from the emission of CO2, N2O and CH4 (Maibach et al., 2008:71f.). Unlike the other factors described, climate change impacts do not concentrate around the place of emission, but are of global nature (ibid.). They include, among others, sea level rise, agricultural impacts, water supply, ecosystems and biodiversity, health impacts, and a higher incidence of extreme weather events (Watkiss et al., 2005:25).

Climate change mitigation is a strategic priority for the European Union (D'Alfonso et al., 2016:261). Transportation is the only sector that so far has not been able to contribute to a reduction in GHG, even when excluding international aviation and shipping, as seen in Figure 1. This highlights the potential of a decarbonisation of the transportation sector for reducing overall GHG emissions.

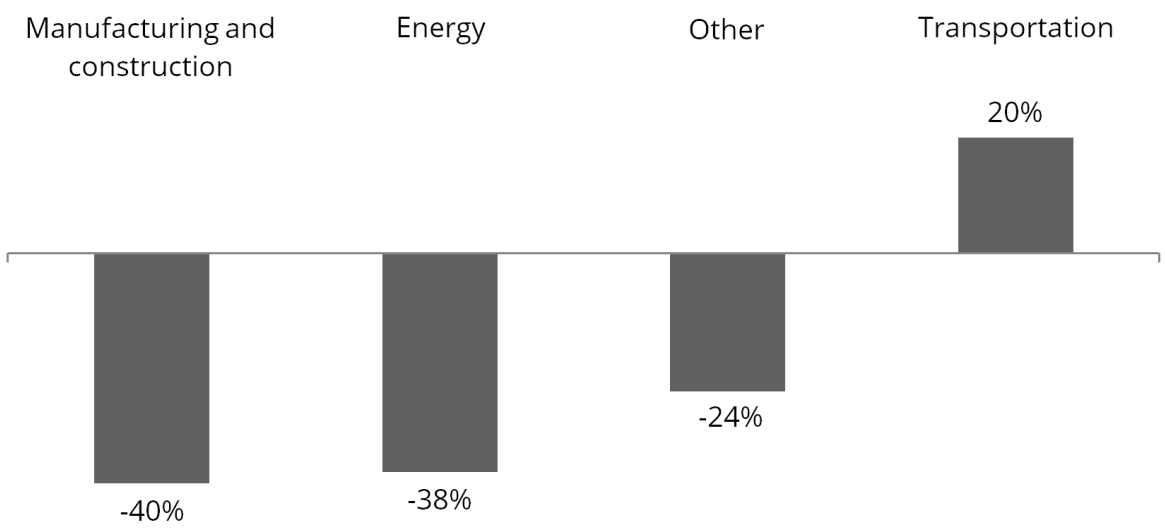

Figure 1: Change of GHG emissions from various sectors in the EU from 1990 to 2018 (own figure based on figures from the European Environment Agency, 2020)

All sources about environmental impacts of HSR reviewed in preparation for the systematic literature review include climate change impacts in their assessments. Some sources even use the terms environmental impact and GHG emissions synonymously (Baron et al., 2011:34f.; R. Zhang et al., 2019:10). The general expectation, as laid out in chapter 1, is that the introduction of HSR leads to a shift in transportation demand from air and road to rail transport. Since HSR is associated with lower climate change impacts per passenger kilometer (Baron et al., 2011:33f.; European Commission, 2010:15), this could lead to an overall reduction in climate change impacts.

LAP includes a variety of pollutants transmitted through air. The European Environment Agency (2015:9) highlights Sulphur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM) as important pollutants in the transportation sector. In the context of a LCA of a planned HSR line in California, Chester & Horvath (2010:2) include SO2, CO, NOx, volatile organic compounds and PM10. Comparing air transport and HSR, D'Alfonso et al. (2016:264) include hydrocarbons (HC), CO, NOx, SO2 and PM. Relevant amounts of air pollutants can be emitted during infrastructure or rolling stock construction as well as power generation and operation, for example as a byproduct of abrasion, combustion or power generation processes (Chester & Horvath, 2010:5). They have in common that they are detrimental to human health (European Environment Agency, 2015:13) and that their concentration and as a result their negative effects are diminishing with increasing distance to the point of emission, hence the term "local". Not just the amount of emission, but also route alignment, surrounding population density and local ventilation conditions are key determinants with regard to LAP impacts. This shows that the severity of the impact of HSR on human health through LAP is largely dependent on the site of

emission. The same applies to health impacts from LAP emissions of alternative modes of transportation. Similar to biodiversity, LAP assessments are therefore not well suited for comparing HSR with alternative modes of transportation.

Noise can be defined as "unwanted sound" (Berglund et al., 1999:vii). Like with LAP, its most relevant effect is the negative impact on human health (ibid.; Department for Transport, 2019:7), and the effect diminishes with increasing distance to the source of emission. Therefore, concerning intermodal comparisons, the same observations as for LAP apply.

Soil resources can be polluted by various air pollutants mentioned under LAP. "The most important negative effects of traffic on soil [however] come from the emission of heavy metals and polycyclic aromatic hydrocarbons [...]" (Maibach et al., 2008:90). They endanger plant and animal life and soil fertility as well as human health (ibid.). The impact of soil pollution is even more locally constrained than that of LAP or noise. For rail and road transport, Schreyer et al. (2006) compile data from various sources up to which distance from the track or road soil pollution can exceed legal limits. For road and rail transport, they quote a maximum distance of 25 m and 10 m respectively (ibid.:116). Considering the operation phase, external costs of rail compared to road transport in terms of soil pollution are small: the authors calculate the external costs for passenger rail on soil to be 0.01 Rp./pkm; that is less than 0.0001 €/pkm. In comparison, coaches are calculated to cause 0.14 Rp./pkm in external costs on soil quality (ibid.:166). Depending on the regulatory framework, soil pollution caused by infrastructure construction is also negligible and poses an internal cost to the building company (ibid.:111). Because of its local nature, the same observations as for LAP and noise also apply to soil pollution. Additionally, the impact of rail transport on soil quality is miniscule and the external costs of alternative modes of transportation for soil quality are small compared to their external costs in other areas. I therefore also exclude soil pollution from the systematic literature review.

Water resources are closely interlinked with soil resources and can be damaged by the same pollutants (Maibach et al., 2008:90f.). Like soil, water resources are critical for the natural environment as well as human health (ibid.). The spatial distribution of water pollution is less confined. It depends on local conditions such as the structure and flow of bodies of surface and ground water. However, like with soil quality, the impact of transportation on water quality is small compared to other factors. Schreyer et al. (2006:116) estimate the external costs of both road and rail transport on water resources at 0.00 Rp./pkm. Contrary, the Department for Transport (2019) dedicates a separate chapter to the appraisal of impacts on the water environment, indicating that transportation has a relevant adverse impact on water resources. Overall however, only a small number of sources consider impacts of HSR or transportation in general on water resources at all. Those that do present small impacts compared to other factors. I therefore exclude it from the systematic literature review.

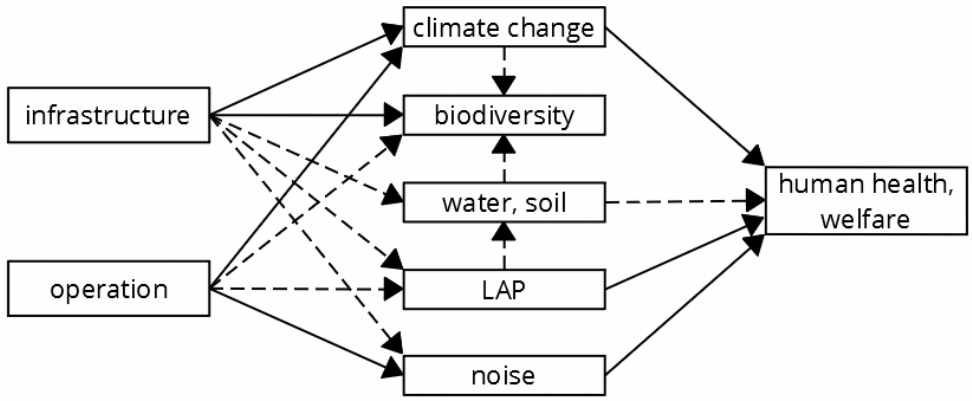

Figure 2: Causal chains of environmental factors affected by HSR. Solid arrow: strong relationship, dashed arrow: weak relationship (own figure)

I find that biodiversity, LAP, noise, soil and water pollution are not well suited for assessing the interrelation of environmental and accessibility impacts of HSR, such as mode shift, induced demand, or complementary effects, on a transportation system level. That is because the impacts on these environmental factors are either negligible in size, highly dependent on local conditions or largely unaffected by HSR infrastructure and operation. Because of climate change's global nature, its close relation to HSR's intermodal relationship with air transport, its ability to capture effects of induced demand and complementary effects and because global warming is an important environmental argument made in favor of HSR, this paper focuses on climate change impacts. Values for specific carbon emissions (carbon intensity) of HSR and alternative modes are gathered in research field 2. Research fields 3, 4 and 5 then deal with impacts of HSR on transport volumes, which in combination with research field 2 allows drawing conclusions regarding the overall environmental impact.

3 METHODOLOGY

I carry out a systematic literature review to generate a representative literature corpus. Queried databases are Academic Search Elite (ASE), Transport Research International Documentation (TRID) and Web of Science (WOS). I construct two search strings, the first one geared toward complementary and competition impacts and the second one toward climate change impacts of HSR. The search strings are based on the five research fields developed from the systematization of environmental and accessibility impacts as well as the preliminary literature. The two search strings and three queried databases result in six queries. For WOS and ASE, I enter the strings as "All fields" requests, for TRID as "Keywords". Results were restricted to a timespan from 2005 to 2020. The queries took place on November 18, 2020. The search strings as well as the number of unrefined and refined results are shown in Table 1.

Table 1: Database queries and results

		Access		Climate
Search string		("high-speed rail" OR "high speed rail" OR "HSR") AND ("impact*" OR "effect*") AND		
		("mode shift" OR "induce*" OR "competition" OR "complementary*")		("Greenhouse Gas*" OR "GHG" OR "CO2" OR "climate")
Refinement		unrefined	refined[3]	unrefined (results sufficiently specific)
No. of results by database	ASE	*407*	168	68
	TRID	*227*	69	78
	WOS	*620*	202	180

The six lists of results are exported to the literature management software Zotero. I further refine the results by judging the potential relevance of the finds to the research questions based on their title and abstract. Potentially relevant finds from the lists of results are moved to corresponding folders. To ensure that doublets (i.e. finds that show up in two or more lists of results) are uniformly categorized as potentially relevant or not relevant across the six lists of result, the titles of all sources identified as potentially relevant are compared to those identified as not relevant. Next, I merge the six lists of potentially relevant finds. The 159 potentially relevant finds across the six searches result in a total of 95 potentially relevant, unique sources, after eliminating doublets,

[3] Refinement: ASE: thesaurus subject "high speed trains", TRID: subject areas "Transportation (General)", "Economics", "Environment", WOS: Transportation, Economics, Transportation Science Technology, Environmental Sciences, Geography, Environmental Studies, Engineering Environmental

triplets etc. Table 2 contains the number of finds and unique sources by the number of times they show up among the six queries.

Table 2: Number of unique finds, doublets, triplets etc.

No. of times source is found	1	2	3	4	5	6	Sum
No. of finds	51	62	27	8	5	6	159
No. of unique sources	51	31	9	2	1	1	95

The overlap between the six searches (47.3 % of unique sources were included in more than one list of results) demonstrates that the systematic literature review is able to capture a sufficiently large share of potentially relevant sources among the existing literature. Of the 95 unique sources, 19 were not retrievable online, via the SLUB library or by contacting the authors. 77 sources were retrievable via at least one of those means. Among them, six sources were already included in the preliminary research prior to the systematic literature review, demonstrating that the search strings of the systematic literature review accurately target the research field of this paper. I decide to add two relevant sources from the preliminary research that do not show up as results in the systematic literature review. This results in a literature corpus of 79 sources to be analyzed for the main part of this research paper.

4 RESULTS

4.1 DESCRIPTIVE STATISTICS

I categorize the 79 sources from the literature corpus according to the following criteria: year of publication, spatial context, methodology and whether they contain information relevant to one or several of the five research fields. Six sources contribute to research field 1, 19 to 2, 36 to 3, 18 to 4 and 19 to 5. 18 sources do not contain relevant information to any research field research. Those research fields, as set out in chapter 1 and 2.3, are:

1. Spatial equity
2. Carbon intensity
3. Mode shift to HSR
4. Induced HSR demand
5. Complementary effects

Figure 3 depicts the number of sources by year of publication, demonstrating the high degree of currency of the literature corpus. Table 3 contains the number of sources by spatial context, aggregated on the continental level, indicating that existing research focuses heavily on Europe and Asia, particularly China. This is unsurprising, since HSR is most developed in these markets, and resonates with findings of other meta-studies (Catalano et al., 2019). I also classify sources by their dominant methodology. Table 4 contains the delimitation between the different research approaches and how many sources fall into each category. The most common methodologies in the literature corpus are regression analyses (23 sources), economic models and simulations (17) and LCA (13). More specifically, many sources contributing to research fields 3 and 5 employ panel regression analyses to empirically evaluate the relationship between HSR service on one hand and air traffic on the other. Economic models and simulations are predominantly used for research relevant to research field 3. Sources that carry out LCA primarily contribute to research field 2.

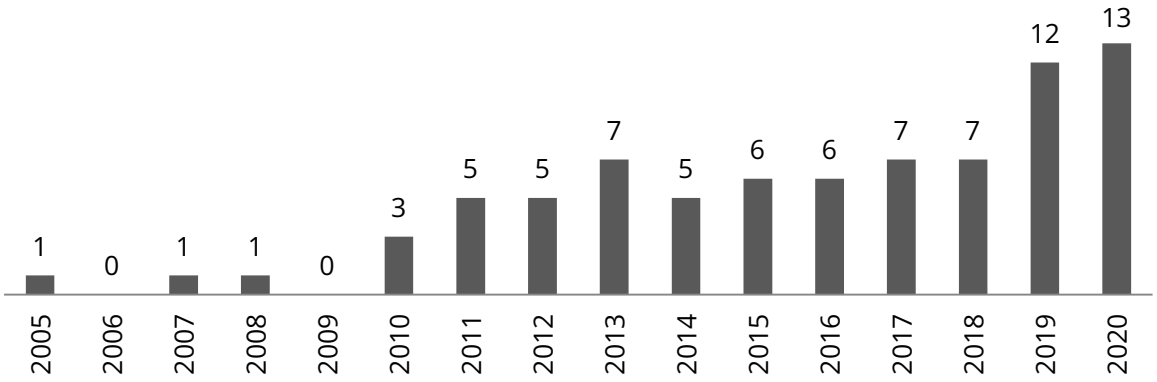

Figure 3: Number of sources in the literature corpus by year

Table 3: Spatial context of sources in the literature corpus

Region	Global	E. Asia	Europe	N. America	Other	sum
Number of sources	15	22	33	5	4	79
Share [%]	19	28	41	6	5	100
Studies relating to two or more regions are classified as "global".						

Table 4: Delimitation of methodological approaches and number of sources

Methodology	Number	Explanation
Regression	23	Data from transportation markets affected by multiple HSR projects is analyzed. Generates insight into the general impact of HSR expressed in model coefficients.
Economic model/simulation	17	A theoretical economic model is constructed and/or applied to a specific context. Includes transportation models.
Live-cycle assessment	13	The environmental impact of a specific HSR project is estimated over the project's life-cycle.
Case study	8	Other types of case studies[4] that do not fit into one of the other categories.
Survey	8	Generate quantitative data by surveying (potential) transportation system users.
Meta-study	5	Compile data from other sources or summarize the current state of research for the scientific community.
Accessibility model	3	Compute (changes in) accessibility measures due to specific projects or schemes.
Handbook	3	Compiles data from other sources or redacts the current state of research for a non-scientific community.
Other	3	Methodological approaches that do not fit into any of the categories above.

[4] For the purpose of this paper, I refer to case studies to indicate "that the research investigates a single phenomenon, instance, or example" (Gerring, 2004:342). For the purpose of this paper, case studies therefore examine (the impact of) one or a very limited number of HSR projects. Other methodological approaches (e.g. LCA) also constitute case studies, but are listed under the more precise category.

Table 5: Sources in the literature corpus by first author, year of publication, spatial context, methodology and research field

First author	Year	Spatial	Methodology	Field 1 spatial equity	Field 2 carbon intensity	Field 3 mode shift to HSR	Field 4 induced HSR	Field 5 induced other
Total number of relevant sources by research field				6	19	36	18	19
Sources added from preliminary literature study								
Chen	2019	East Asia	regression			x		
DG MOVE	2014	Europe	handbook		x			
Sources from the systematic literature review								
Adler	2010	Europe	economic mod/sim					
Albalate	2014	Europe	regression			x	x	x
Alvarez	2010	Europe	other			x	x	
Baron	2011	global	LCA, case study		x	x	x	
Baumeister	2019	Europe	case study		x	x		
Bergantino	2020	Europe	survey			x		
Borsati	2020	Europe	regression					x
Bueno	2017	Europe	LCA		x	x	x	
Capozza	2016	Europe	regression					
Cascetta	2015	Europe	survey, economic mod/sim			x	x	
Cascetta	2020	Europe	accessibility model	x				
Castillo-Manzano	2015	Europe	regression			x		
Cavallaro	2020	Europe	accessibility model	x				
Cetkovic	2020	Europe	other			x		
Chang	2011	N. America	LCA		x			
Chen	2017	East Asia	regression			x		
Cheng	2020	East Asia	LCA		x			
Chester	2010	N. America	LCA		x			

First author	Year	Spatial	Methodology	Field 1 spatial equity	Field 2 carbon intensity	Field 3 mode shift to HSR	Field 4 induced HSR	Field 5 induced other
Chester	2013	global	handbook			x		x
Clewlow	2014	Europe	regression			x		
Couto	2008	Europe	regression					
D'Alfonso	2015	global	economic mod/sim			x	x	
D'Alfonso	2016	Europe	economic mod/sim		x	x	x	x
Dalkic	2017	other	survey		x	x	x	
Danapour	2018	other	survey					
de Bortoli	2020	Europe	LCA		x			
Dobruszkes	2011	Europe	case study			x		
Dobruszkes	2013	Europe	meta-study			x	x	x
Dobruszkes	2014	Europe	regression			x		
Feng	2017	East Asia	regression					
Fu	2013	East Asia	LCA		x			
Givoni	2007	Europe	case study			x		
Givoni	2013	global	meta-study			x	x	x
Gu	2020	East Asia	regression			x		x
Hayamizu	2018	East Asia	survey					
Janic	2011	Europe	economic mod/sim					
Jehanno	2011	global	handbook		x			
Jiang	2014	global	economic mod/sim			x	x	x
Jiang	2016	global	economic mod/sim					
Jones	2016	Europe	LCA		x			
Kommapalati	2019	N. America	LCA		x			
Li	2018	East Asia	regression					
Li	2019	East Asia	economic mod/sim					

First author	Year	Spatial	Methodology	Field 1 spatial equity	Field 2 carbon intensity	Field 3 mode shift to HSR	Field 4 induced HSR	Field 5 induced other
Li	2020	East Asia	economic mod/sim, regression	x				
Lin	2020	East Asia	LCA		x			
Liu	2019	East Asia	regression			x		x
Matute	2015	N. America	LCA		x	x		
Mikio	2018	global	economic mod/sim					
Miyoshi	2013	Europe	LCA			x	x	
Moyano	2017	Europe	case study	x				
Nelldal	2012	Europe	economic mod/sim					
Olugbenga	2019	global	meta-study		x			
Pagliara	2012	Europe	survey					
Pita	2012	Europe	case study			x	x	
Prussi	2018	Europe	case study			x		
Robertson	2013	other	case study		x			
Robertson	2017	other	LCA					
Socorro	2013	global	economic mod/sim				x	x
Su	2019	East Asia	regression					x
Su	2020	East Asia	regression					x
Sun	2017	global	meta-study			x		x
Terpstra	2015	Europe	regression					x
Wan	2016	East Asia	regression			x		x
Wang	2019	East Asia	regression					
Wang	2020	Europe	economic mod/sim			x	x	x
Westin	2012	global	other		x	x	x	
Xia	2016	global	economic mod/sim					x
Yang	2018	East Asia	regression			x		

First author	Year	Spatial	Methodology	Field 1 spatial equity	Field 2 carbon intensity	Field 3 mode shift to HSR	Field 4 induced HSR	Field 5 induced other
Yang	2019	East Asia	regression					
Yang	2020	East Asia	economic mod/sim			x		x
Yao	2005	East Asia	economic mod/sim, survey				x	
Zanin	2012	Europe	economic mod/sim			x		
Zhang, F.	2018	global	regression					
Zhang, A.	2019	global	meta-study	x		x		x
Zhang, D.	2019	N. America	survey, regression				x	
Zhang, R.	2019	East Asia	regression					
Zhu	2015	East Asia	accessibility model	x				

4.2 FIELD 1: SPATIAL EQUITY

As set out in chapter 2, spatial equity is a political objective. Improving the accessibility of peripheral regions means that people and businesses there have easier access to markets as well as specialized goods, services and infrastructure not available locally. Policy makers therefore might champion HSR as a tool to foster economic development and align living conditions in peripheral regions with those of metropolitan areas (A. Zhang et al., 2019:11).

In this chapter, I look at the six relevant sources from the literature corpus in this research field to assess what the introduction of HSR can mean for the accessibility and equity of living conditions in peripheral regions and to identify methodological shortcomings as well as further research needs.

4.2.1 Studies

All studies analyzed look at accessibility in terms of actual HSR service instead of mere infrastructure. Moyano & Dobruszkes (2017) underpin the relevance of this approach in their article "Mind the Service! High-speed rail cities bypassed by high-speed trains". They identify three situations where a city might lose existing long-distance rail service: cities with HSR stations where trains do not stop, cities bypassed by new HSR lines altogether, and border stations as customary stops and change of engine become redundant (ibid.:6). Bypassing intermediate cities is especially tempting for train operators when travel time between two metropolises on each end of the line is on the edge of being competitive with air transport, or between 120 and 150 minutes (ibid.:5). These phenomena have been described as the "tunnel effect", leading to a more polarized city network where large cities profit disproportionally from the introduction of HSR services (ibid.:6).

Moyano & Dobruszkes (2017) develop a characterization of four types of smaller intermediate cities that might not profit as much from HSR introduction or expansion as hoped by policy makers. Ebbsfleet in the UK on the London-Paris route is presented as an example for a city that is too small to retain international services, albeit there are frequent high-speed services to and from London (ibid.:8ff.). On the other hand, the French city of Lille, situated strategically between the Channel Tunnel, Brussels and Paris, is comparatively large, but most international services nevertheless do not call at Lille. This is because the demand generated by Lille is dwarfed by that of London and Paris at either end of the line. Also, travel time between those two cities is at the edge of allowing competition by airlines, at 2 hours and 16 minutes. The case is similar for London-Brussels and Brussels-Paris services (ibid.:10ff.). The example of the French town of Le Mans demonstrates that the expansion of HSR lines can result in a reduction of services at former end points of HSR lines. Up to 2017, the LGV Atlantique ended shortly before approaching Le Mans, and HSR services from Paris to Rennes would pass through and stop in the city. The city enjoyed a high level of service

considering its size. With the expansion of the HSR line to Rennes a bypass was built and calling at Le Mans now poses a detour via connecting branch lines. Local authorities came to an agreement with SNCF to ensure that until 2022, HSR services are not reduced beneath their level during winter 2001/2002, but it's unclear how frequent the city will be served after 2022 (ibid.:15ff.). The fourth case study looks at Liege, Belgium. Among several reasons similar to the situation of Lille, the lack of economic development in Liege after the introduction of HSR is cited as being detrimental to future frequency of service. While many resources were spent on constructing a new and elaborate HSR station, urban and regional planning did not accomplish an inflow of international firms and skilled workers that generate demand for international HSR services. As a result, the city might be bypassed by future HSR services (ibid.:17ff.). The authors point out that in general, while local authorities might be able to influence and even co-fund HSR infrastructure with the aim to secure some level of HSR service, they do not control HSR operation since train operators are either supervised by the state or subject to market mechanisms. They find it debatable whether local authorities should have some influence on HSR service (ibid.:21).

A. Zhang et al. (2019) carry out a meta-study looking at the economic impact of HSR accessibility on cities' economies. In the relevant section, they compare findings of 15 empirical papers looking at various countries. They describe two seemingly contradicting predictions: The first one is the "siphon effect", "that is, large cites attracting activities away from small cities" (ibid.:2). Increasing accessibility of second-tier cities would therefore ease the flow of resources (e.g. talents, investments and purchasing power) from small to large cities, "as the latter possess [...] factors that improve efficiency of doing business" (ibid.:11)[5]. In other words, HSR extends the catchment areas of metropolises, improving their agglomeration benefits even further compared to second tier cities. Contrary to the siphon effect, there is also a spillover effect. It postulates that connecting second-tier cities with a metropolis can cause growth from the metropolis to spillover onto the second-tier city, as people and companies try to avoid the negative agglomeration effects (such as congestion or high land prices) while still having access to the resources and markets of the metropolis (ibid.:16f.).

A. Zhang et al. (2019) attest that most of the sources examined look at either one or the other of the two effects, only measure net effects, and include a limited subset of cities. That is why the literature yields mixed results. According to the authors, in reality both effects take place and one might outweigh the other depending on whether the agglomeration force or the dispersion force dominates (ibid.:11,14). They develop a system of different types of cities and regions that might be affected by HSR, which is depicted in Figure 4, to be able to coalesce the seemingly contradictory findings.

[5] This is not to be confused with the tunnel effect mentioned earlier, which describes the long-term self-reinforcing cycle of second-tier cities losing HSR services and failing to generate sufficient HSR demand.

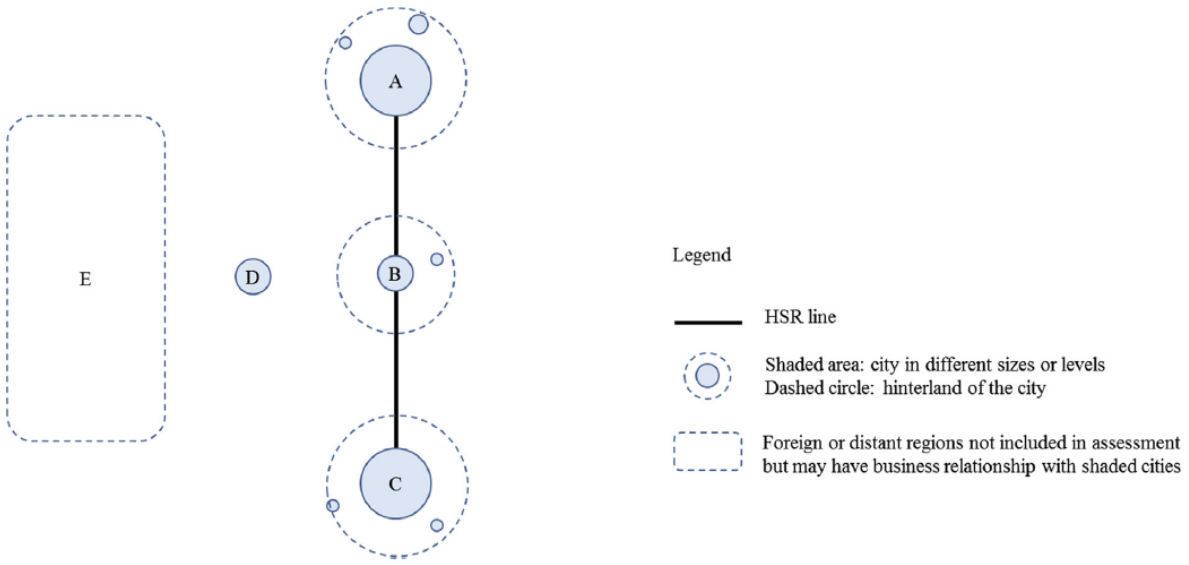

Figure 4: Conceptual illustration of cities/regions affected by HSR (A. Zhang et al., 2019:15)

First, they compare cities with and without HSR (A, B or C vs. D). Unsurprisingly, the sources agree that HSR introduction increases the spatial divergence between places that are accessible via HSR and those that are not (ibid.:15f.). The second comparison however, looking at HSR cities with different levels of development (A or C vs. B), yields more differentiated results. Depending on the size and structure of B's economy, increasing accessibility increases the siphon and the spillover effect at different rates. The majority of studies examined by A. Zhang et al. (2019) find that the spillover effect dominates, meaning that the introduction of HSR raises spatial equity. However, for very small intermediate towns results are mixed, with strong negative (mining regions in France) and positive examples (Montabaur and Limburg in Germany) (ibid.:16).

Generally, whether small and medium towns can profit from enhanced HSR accessibility does not depend primarily on their size. The authors conclude that in order for small or medium sized towns to profit from HSR (i.e. the spillover effect dominating over the siphon effect), three key factors must be met. They tend to profit when one can reach larger cities within about 2 hours via HSR, when they have a well-developed service-oriented sector, and when the larger city's economy is mature enough that dispersion forces outweigh agglomeration forces (ibid.:16f.). This resonates with the findings of Moyano & Dobruszkes (2017) concerning Lille and Liege.

Three of the six studies from the literature corpus dealing with research field 1 calculate accessibility measures for different HSR scenarios. Cascetta et al. (2020) compute HSR accessibility for the 102 administrative provinces of Italy based on three scenarios: 2008 (before HSR), 2018 (current HSR network, ex-post) and the design scenario (future comprehensive HSR network, ex-ante). After testing various travel cost measures, they choose rail generalized transportation costs as travel costs input, transformed using a negative exponential decay function. The 102 traffic

zones are weighted using the total number of employees in industry, trade and services, transformed using a power decay function (ibid.:417). Accessibilities in 2018 and the design scenario are then compared to accessibility in 2008. Figure 5 shows which regions experienced weak (white) or strong (blue) improvement in HSR accessibility. No traffic zone experienced a decline in accessibility, although the low spatial resolution might conceal declines in accessibility in some regional centers previously served by conventional long-distance trains.

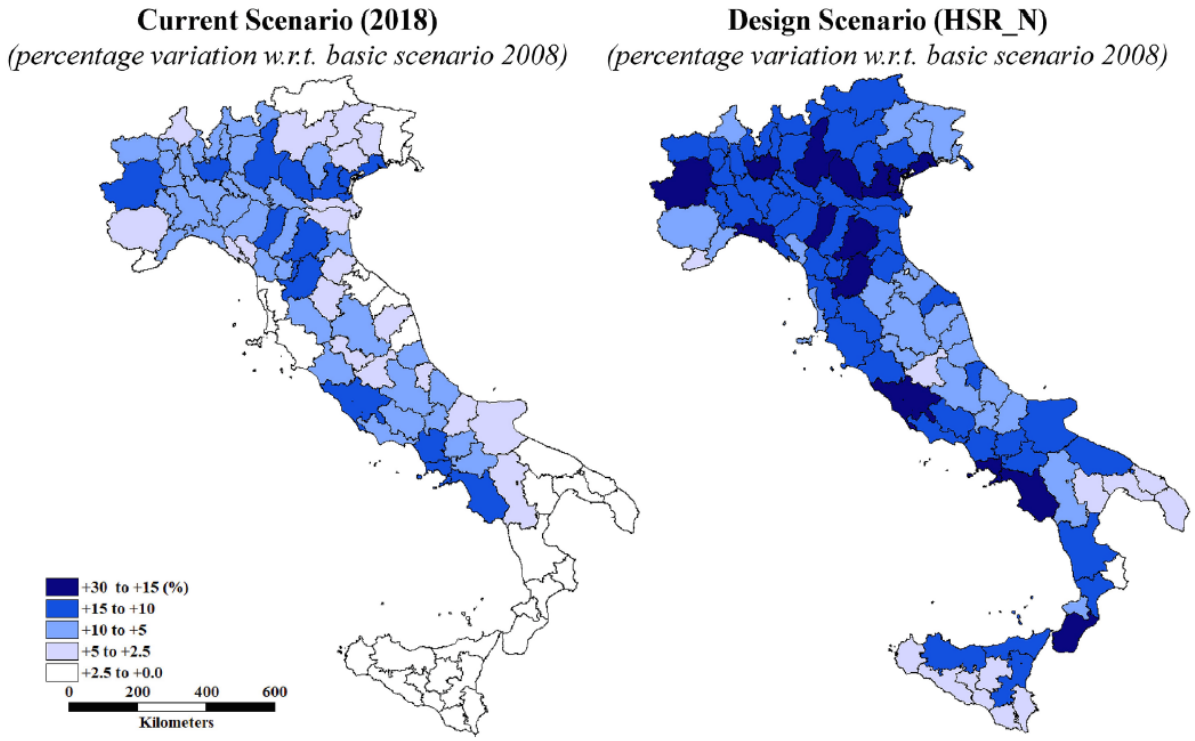

Figure 5: Rail accessibility's percentage variation with respect to basic scenario in 2008 (Cascetta et al., 2020:418)

Employing an advance unique among the literature corpus, Cascetta et al. (2020) then calculate Gini-coefficients for the spread of the accessibility measure among the 102 traffic zones in each scenario to investigate whether the accessibility of regions equalizes or diverges. Between the 2008 and 2018 scenario, the Gini-coefficient for accessibility based on generalized costs rises from 0.120 to 0.125, indicating a slight rise in spatial inequity. The design scenario with its more comprehensive network yields a Gini-coefficient of 0.080, indicating a rise in spatial equity both compared to the 2008 and 2018 scenario (ibid.:425). This illustrates a trade-off between efficiency and equity: the most profitable routes that are built first are likely to connect large urban centers with each other, further improving their accessibility while not benefitting peripheral regions. As the network is expanded further and routes that generate less demand are constructed, peripheral regions also gain direct access to the HSR network, raising spatial equity again (ibid.:426).

Zhu et al. (2015) calculate the accessibility surface of China for 2009 and 2013, using economic potential (E_i) as the accessibility measure. They transform travel time (t_{ij}) using a simple power decay function (see chapter 2.3) and weight with the untransformed GDP (M_j) of every destination.

Equation 7: Economic potential (Zhu et al., 2015:2110)

$$E_i = \sum_{j=1}^{m} M_j / t_{ji}$$

They demonstrate that the economic potential improves for all cities, but that large, already wealthy and well-connected cities benefit disproportionately, leading to a greater spatial inequity in China (ibid.:2110f.). However, their calculation is based on station-to station travel time and takes place at the city level (which in China can cover areas comparable to provinces or states in other countries), which allows for broad statements regarding accessibility on the national level but might conceal local declines in accessibility due to a reduction of service on CR lines.

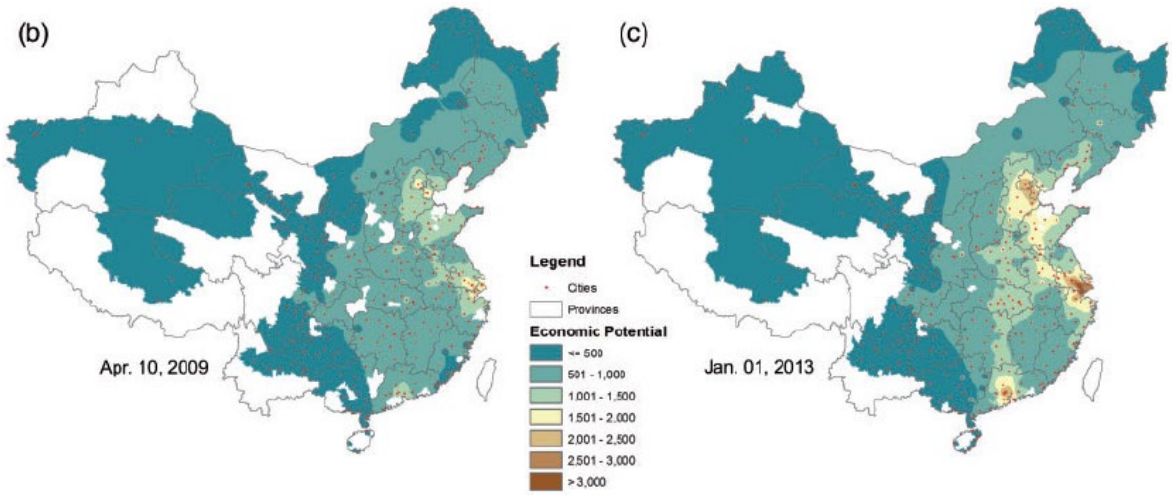

Figure 6: Economic potential in China in 2009 (b) and 2013 (c) (Zhu et al., 2015:2109, cropped)

Cavallaro et al. (2020) look at equity in HSR in Italy from both a spatial and a social perspective. For spatial equity, they calculate a spatial equity index for specific origin-destination-connections. This so-called SpREI index takes into account the population of the origin (p), travel time to a given place (t) and the number of transfers involved (c) for a given year (A or B). To account for different numbers of working days in their observation years, they also introduce two coefficients α and β that assign different weights to connections performed during working days or weekends. The

higher the score, the less attractive the trip is. The SpREI indexes before and after HSR introduction are compared and the variation is expressed as a percentage value. The higher this $SpREI_0$ percentage, the larger the increase in accessibility (Cavallaro et al., 2020:331f.). The SpREI index is not an accessibility measure in the sense that I describe in chapter 2.3, but allows similar interpretations.

Equation 8: SpREI index (before) (Cavallaro et al., 2020:332)

$$SpREI_A = \frac{[\propto c_{WA} + \beta(365 - \alpha)c_{hA}]}{ln\{p_A * [\propto \mathrm{t}_{wA} + (365{-}\propto) * t_A]\}}$$

Equation 9: SpREI index (after) (Cavallaro et al., 2020:332)

$$SpREI_B = \frac{[\propto c_{WB} + \beta(365 - \alpha)c_{hB}]}{ln\{p_B * [\propto \mathrm{t}_{wB} + (365{-}\propto) * t_B]\}}$$

Equation 10: SpREI index (comparison) (Cavallaro et al., 2020:332)

$$SpREI_0 = \frac{SpREI_A - SpREI_B}{SpREI_B}$$

The authors calculcate $SpREI_A$, $SpREI_B$ and $SpREI_0$ values for four cities in the Lower Piedmont and Ligurian area in northern Italy and their connection to Rome. SpREI indeces rose by 243 %, 216 % and 709 % for Alessandria, Asti and Turin respectively, but only by 69 % for Genoa (ibid.:335). HSR therefore improved accessibilty of all four cities to Rome, but Genoa could not benefit as much as its peers because a trip to Rome now involves an additional transfer since the city is not located on a HSR line (ibid.:336). The authors conclude that to foster spatial equity, integration of HSR with the secondary transport networks is crucial. They also point out that the different territorial competence for HSR and regional transport might impede this integration (ibid.:338).

The last study from the literature corpus relevant in this research field was put forward by Li et al. (2020). Unlike the previously mentioned sources that calculate accessibility measures, the authors looked at the change of CR passengers' welfare due to the introduction of HSR. While this study does not focus on analyzing spatial equity, it generates some findings that are relevant to this field. Li et al. (2020) construct a passenger utility model for the mode choice of intercity travel (air transport, CR, Bullet Train and HSR) in China. They then estimate the model parameters using data from 273 city pairs (ibid.:12ff.). In other words, they estimate passengers' utility of service frequency, travel time and number of seats. They then develop an econometric model and carry

out a regression analysis to calculate the impact of HSR introduction on conventional train operations using the same data (ibid.:16ff.). They find that the introduction of HSR in China caused a reduction in CR service frequency but not a reduction of travel time (which could have been expected due to freed up capacity on congested legacy lines) (ibid.:20). Lastly, by combining these results, they calculate the welfare change of CR passengers and non-CR passengers caused by the introduction of HSR. They find that the average per-passenger loss of welfare for passengers that use CR after HSR introduction is 0.87 US$ on routes shorter than 1000 km and 0.29 US$ on routes longer than 1000 km (ibid.:23). This amounts to a total welfare loss of 587 million US$ in 2017 in China. This number poses a lower bound, since CR passengers who ceased to use CR due to declining service are not included (ibid.:22). On the other hand, former CR or new passengers who use HSR experience an average welfare gain of 13.29 US$ and 7.86 US$ per passenger on routes shorter or longer than 1000 km respectively (ibid.:26), amounting to a total welfare gain of 6.11 billion US$ in 2017 in China (ibid.:27).

The authors conclude that the welfare benefit of HSR might be overestimated by around 8 % (ibid.:28). This is relevant to research field 1 because it provides a frame of reference for the scale of welfare loss due to a decline in CR service, which is more relevant for cities and regions bypassed by HSR lines, compared to the welfare gain due to HSR introduction, which is more relevant for cities and regions along HSR lines. One can assume that the ratio of potential loss of welfare due to the introduction of HSR in peripheral regions compared to the welfare gain in large cities is much smaller than 8 %, because the decline of CR service and the improvement of HSR service both affect peripheral and well accessible regions.

4.2.2 Methodological Remarks

One shortcoming of all six sources analyzed in this section is that they only consider one mode of transportation, namely rail. It is unsurprising that every source deals with HSR, as this was specified in the search strings for the systematic literature review. However, no source looks at the interaction of HSR with other modes (other than CR). For example, the introduction of HSR would likely affect accessibility calculated over multiple modes weighted by mode share positively. But perhaps the higher reliance on private transport in rural areas of developed countries could mean that the improvement in overall accessibility due to the introduction of HSR would carry less weight there than in urban centers. HSR could also enhance the accessibility of peripheral regions to specific onward transportation services only available in large urban centers, such as international airports. If such specific structure sizes were taken into account for accessibility instead of more evenly distributed ones such as population or GDP, the impact of HSR on spatial equity might turn out differently. The relevance of spatial resolution in accessibility analyses (A. Zhang et al., 2019:14) becomes apparent when scrutinizing the results of Cascetta et al. (2020), Cavallaro et al. (2020) and Zhu et al.(2015).

4.2.3 Interim Conclusions

All case studies find that the expansion of HSR systems improves accessibility across the study area. However, it usually increases the difference in accessibility of peripheral and central regions. This is because large and already well-connected cities profit disproportionately. To increase the equality of regional accessibility using HSR, the network would have to be so extensive that routes and services are unlikely to be economically feasible, highlighting a trade-off between equity and efficiency. For small intermediate cities, retaining HSR service in the long-term can be challenging. To secure service, local stakeholders would need influence on (national) train operating companies. Integration of HSR with the secondary transport network is key to ensure seamless connections and to spread HSR benefits to areas not directly accessible by HSR.

Changes in accessibility can impact economic development and equity of living conditions in several ways, depending on the type of city. Smaller cities along HSR lines can profit from HSR if they are within two hours of a larger city, have a well-developed service-oriented sector, and when the larger city experiences negative agglomeration effects. These factors can lead to a spillover-effect of economic activity and growth from the metropolis to the secondary city. On the other hand, if these requirements are not met, connecting a smaller city to a metropolis can hinder its development as the siphon-effect might outweigh the spillover-effect.

I identify several research gaps in the reviewed literature. No study computes accessibility over more than one mode. The higher car dependency of peripheral regions in developed countries might mean that the impact of HSR on multimodal accessibility measures is weaker in such regions than in urban centers, further widening the discrepancy between urban and peripheral regions' accessibility improvements from HSR. Future studies should test the scale and relevance of this impact. In addition, to better capture the role HSR might play in improving peripheral regions' access to services unique to major urban centers, such singular structure sizes should be included alongside more evenly distributed measures such as GDP or population. To verify that HSR does not lead to a reduction in absolute accessibility of some places, accessibility analyses such as from Cascetta et al. (2020), Cavallaro et al. (2020) and Zhu et al. (2015) should be repeated using a finer spatial resolution and including ingress and egress journeys. Finally, the research of Li et al. (2020) provides valuable insight into comparing the scale of welfare loss of CR passengers due to a decline in CR service against the welfare gains due to HSR. It is however limited to the Chinese context. Similar studies for other countries could provide insight into the upper bound of the ratio of potential loss of welfare of passengers in peripheral regions compared to the welfare gain of passengers in large cities due to the introduction of HSR, especially if the changes in welfare were to be calculated separately for central and peripheral regions.

4.3 FIELD 2: CARBON INTENSITY

Carbon intensity is an important input to determine the net climate change impact of a transportation system. In this chapter, I provide an overview over value ranges for the carbon intensity of HSR and alternative modes as well as the methodologies used in the literature. By far the most common methodology used in this context is the Life-Cycle Assessment (LCA). LCA allow quantifying emissions throughout all stages of a transportation system's life cycle and from its various components. There are two types of LCA: process-based and economic input-output analysis-based. Process-based LCA allow for a detailed assessment but require large amounts of data. Economic input-output analysis-based LCA calculate impacts on an industry-sector level, thus requiring less detailed data but only allow for rough system-level comparisons (Jones et al., 2016:5f.; Olugbenga et al., 2019:9). All studies included in the literature corpus carry out process-based LCA unless mentioned otherwise.

I divide the sources analyzed for this chapter into three groups, based on the scope of their LCA or other respective approach. First, I look at studies that only regard operation of HSR (or alternative modes), followed by studies focusing on the embodied emissions in HSR infrastructure. In the third section, studies with comprehensive approaches including both operation and construction are analyzed. Finally, I convert the different values for carbon intensity from the literature corpus to a set of comparable units. This allows me to draw conclusions how HSR compares to alternative modes in terms of overall carbon intensity and on what parameters this judgment depends.

4.3.1 Operation

Alvarez (2010) looks at the energy consumption of HSR trains compared to CR trains and alternative modes in Spain. He compiles data about vehicle energy consumption and operation patterns from Renfe and calculates the average energy consumption per passenger kilometer travelled. For HSR, he calculates an energy consumption of 73 Wh/pkm, which is less than for commuter rail, regional rail or conventional long-distance rail services (ibid.:29). He attributes this perhaps surprising finding to the following reasons: lower resistance in curves, regenerative breaks, aerodynamics, fewer stops and shorter time of use of auxiliary services such as air conditioning (relative to distance travelled) (ibid.:30ff.). Based on previous studies by the same author, Alvarez (2010) calculates the average amount of CO2 emissions due to operation over ten domestic routes from Madrid to other Spanish cities for four modes.

Table 6: Carbon intensities due to operation (Alvarez, 2010:33)

Mode	HSR	Coach	CR	Car	Plane
Emissions [gCO2/pkm]	26.7	32.3	37.9	113.0	169.1

D'Alfonso et al. (2016) expand on a previous duopoly study by the same authors by conducting a simulation study on the London-Paris market. Since they are interested in the impact of a marginal substitution of HSR for air transport, they only consider emissions from operation. They assume CO2 emissions of 122 kg per seat on a flight from London to Paris and 15 kg *(av. speed/(250 km/h)) per seat on a HSR train, but do not explicitly name their sources (ibid.:39). Building on their assumptions of an average speed of 250 km/h, a distance via HSR of 492 km and an occupancy rate of 48 % (ibid.:15), one can interpret this as a carbon intensity of HSR of 64 gCO2/pkm. For air transport, they assume a flight distance of 380 km (ibid.:13) and an average occupancy of 70 % (ibid.:15). One can interpret this as a carbon intensity of air transport of 459 gCO2/pkm. This relatively high value can partially be explained by the short length of the flight, where the higher fuel consumption during takeoff carries more weight than for longer flights.

Givoni (2007) evaluate LAP and climate change impacts of HSR and air traffic, also on the London-Paris route and disregarding provision of infrastructure. They use detailed data, differentiated by flight phase and airplane model (ibid.:221). Their figures deviate from D'Alfonso et al. (2016). The authors calculate CO2 emissions of 44.1 kg/seat on an airplane and 7.2 kg/seat on HSR (Givoni, 2007:211). Even when factoring in NOx emissions and the higher GWP of emissions in high altitudes, they calculate only 85.5 and 7.2 kgCO2/seat on airplane and HSR respectively (ibid.:222), which, using flight and HSR route length and occupancy rates from D'Alfonso et al. (2016), translates to carbon intensities of 321 and 30 gCO2/pkm. The methodology of Givoni (2007) appears more plausible and transparent and carbon intensities are more in line with results from other studies in this chapter then those of D'Alfonso et al. (2016).

Dalkic et al. (2017) assess the reduction of CO2 emissions due to two HSR corridors in Turkey. They compile general carbon intensities for the operation phase of four modes from various sources. For the two study corridors, they also calculate case-specific carbon intensities based on the rail vehicles' electricity consumption and the Turkish electricity mix.

Table 7: Carbon intensities due to operation (Dalkic et al., 2017:8,16)

Mode	HSR	HSR ANK-ESK	HSR ANK-KON	CR	Car	Air
Emissions [gCO2/pkm]	4.0 - 32.9	16.7	17.7	50 - 60	104 - 116	99.8 - 168.0

Prussi & Lonza (2018) investigate the potential of GHG emission reduction by substituting intra-EU flights with HSR. To do so, they look at seven highly frequented international routes between hub airports. For every route, they gather data on flight numbers, the mix of aircraft types and passenger numbers and calculate average CO2 emissions per passenger kilometer. The results vary between 111 and 143 gCO2/pkm (ibid.:6). For HSR journeys, they calculate average carbon intensities per kWh for every route depending on the electricity mix in the traversed countries. The resulting carbon intensities of HSR per passenger kilometer range from 15.0 to 33.6 gCO2/pkm (ibid.:7). The authors remark that for the same journey HSR usually involves longer traversed distances than air transport (ibid.:7). Differences in average ingress and egress journey lengths to and from airports and railway stations are also not accounted for.

The last study that only regards emissions from the operation phase was published by Robertson (2013). The author aims to answer the question how many emissions would be avoided if there was a mode shift of 50 % of air traffic to (a proposed) HSR on the Melbourne-Sydney corridor. Assuming an occupancy rate of 81.6 %, electricity consumption of various HSR train-sets (ibid.:401) and a carbon intensity of electricity of 1.07 kgCO2/kWh (ibid.:402), he estimates a carbon intensity of 50 gCO2/pkm. In contrast, he estimates carbon intensity of air traffic to be 90 gCO2/pkm (ibid.:403). He models carbon intensity of both HSR and air transport to steadily decrease from 2010 to 2030 due to advances in fuel efficiency and decarbonization of electricity production (ibid.:403).

Unsurprisingly, studies that disregard emission from infrastructure construction find that HSR is superior to air transport in terms of carbon intensity. Occupancy of rolling stock and the carbon intensity of the electricity mix can cause large differences among these estimates. In the following section, I look at studies that disregard operation of HSR and solely focus on the embodied emissions of HSR infrastructure.

4.3.2 Infrastructure

Chang & Kendall (2011) carry out a LCA of GHG emissions for the construction of the California HSR (CAHSR). They assess three main causes of emissions: material production, material delivery and construction equipment operation. They compile transportation distances, emissions factors and construction intensities (e.g. material usage or soil movement) from comparable projects (ibid.:431). They find that the production of construction materials causes 80 % of emissions, their transport 6 % and operation of construction equipment on site 5 % (ibid.:432). Tunnels and aerial structures contribute 60 % of emissions, despite only accounting for 15 % of total route length. In total, they estimate that the construction of CAHSR emits 2,400 ktCO2eq (ibid.:433). Assuming a route length of 725 km (ibid.:430) and a lifespan of 100 years (Baron et al., 2011:5), this translates to 33.1 tCO2eq/km, year.

The finding that the share of bridges and tunnels is highly relevant for the carbon intensity of infrastructure construction is supported by many other sources. Cheng et al. (2020) carry out an input-output analysis-based LCA for components of HSR infrastructure. They find that bridges account for emissions of 23,000 tCO2/km (not including rails, electronic equipment etc.) (ibid.:9), or 230 tCO2/year, km assuming a life span of again 100 years.

De Bortoli et al. (2020) perform a LCA for the Tours-Bordeaux HSR, climate change impact being one among 13 impacts assessed. They include the phases of construction, maintenance and end of life (ibid.:7ff.). They gather their data mainly from construction reports (ibid.:6). 48 % of (positive and negative) emissions are due to production (i.e. construction) of the infrastructure and 38 % are due to maintenance. 15 % of emissions are caused during the end of life phase, however with a negative sign due to recycling (ibid.:13). Steel and concrete manufacturing are the most important contributing processes during the construction phase (ibid.:16). The total climate change impact is estimated to be 2.75 tCO2eq/km, year, for a single track (ibid.:15). The authors assume a lifespan of major infrastructure components of 100 years (ibid.:3), however calculate the values for a single track railway (ibid.:15). HSR is almost exclusively built as a double-track railway, but major infrastructure components such as dams or bridges cannot be expected to be twice as carbon intensive for a double-track compared to a single-track railway. The study's methodology and data transparency does not enable me to judge whether the provided value for carbon intensity of a single-track railway can simply be doubled to attain values for a double-track railway. I therefore assume a range of 2.75 - 5.5 tCO2eq/km, year for double-track HSR.

Lin et al. (2020) carry out a hybrid LCA (combining elements from both input-output analysis-based and process based LCA) to assess the environmental footprint of the Beijing-Tianjin HSR line. They include all processing stages from resource extraction to end of life and differentiate between seven subsystems such as bridges, rails or stations (ibid.:4). Total emissions of the line's construction are estimated at 3,451 ktCO2 (ibid.:7). Based on a route length of 120 km (ibid.:5) and a life span of 100 years (Baron et al., 2011:5), this translates to 288 tCO2/km, year. Bridges alone account for 63.3 % of emissions (Lin et al., 2020:7). 83.8 % of the route are constructed on such structures (ibid.:5).

The last study that only regards emissions from the operation phase was published by Olugbenga et al. (2019). It is a meta-study on GHG emissions embodied in rail infrastructure (HSR as well as other types of railways), including some sources that are also present in the literature corpus. For HSR, embodied emissions range from 13 tCO2eq/km to 16,940 tCO2eq/km (0.13 to 169.4 tCO2eq/km, year respectively, assuming a life span of 100 years). The upper bound represents a Japanese HSR involving large scale tunneling and construction work (ibid.:13f.). To build a simple linear model that allows for rough estimates of carbon emissions of railway construction, the authors calculate the mean embodied GHG emissions for at-grade HSR infrastructure to be 1,018 tCO2eq/km with a standard error of 224 (ibid.:16,18). Sections involving tunneling create on average 37 times the embodied emissions of at-grade construction (ibid.:18). Bridges are not

accounted for in this estimate. Perhaps surprisingly, embodied emissions of at-grade HSR infrastructure are lower than that of commuter rail, metros or intercity rail (ibid.:16). However, due to more demanding building parameters such as curve radii and gradients, HSR is likely to involve a higher share of elevated or subgrade structures.

The findings in this section demonstrate that infrastructure construction is an important contributor to CO2 emissions of HSR. Carbon intensity of routes can vary strongly depending on the share of bridge and tunnel construction. As total embodied emissions in infrastructure construction are independent from passenger numbers, they are even more relevant to carbon intensities of routes with low ridership. On the other hand, where HSR infrastructure already exists, embodied emissions can be regarded as sunken costs irrelevant to the environmental impact of a marginal substitution of HSR for alternative modes. In the following third section, I summarize comprehensive studies that take into account both infrastructure construction and operation.

4.3.3 Comprehensive Studies

Baron et al. (2011) put forward a detailed assessment of HSR carbon footprints. They carry out ex-ante LCA for four HSR lines: South Europe Atlantic (France), Mediterrean (France), Taipei-Kaohsiung (Taiwan) and Beijing-Tianjin (China). They consider the four phases conception, construction, operation and disposal for both rolling stock and infrastructure (ibid.:3). Lifespans are assumed and emission factors are taken from the Ecoinvent v2.0 database (ibid.:4).

For the construction of the LGV Mediterrean the authors calculate emissions of 17,055.5 tCO2/year, which, at a route length of 250 km (ibid.:20), translates to 68.2 tCO2/km, year. For the construction of the LGV South Atlantic the authors calculate emissions of 17,518 tCO2/year, which, at a route length of 302 km (ibid.:21), translates to 58.0 tCO2/km, year. For the construction of the Taipei-Kaohsiung line the authors calculate emissions of 60,900.75 tCO2/year, which, at a route length of 345 km (ibid.:22), translates to 176.5 tCO2/km, year. For the construction of the Beijing-Tianjin line the authors calculate emissions of 16,263 tCO2/year, which, at a route length of 117 km (ibid.:24), translates to 136 tCO2/km, year. Using passenger numbers for every line, the authors calculate CO2 emissions per passenger kilometer, which are shown in Table 8. Emissions caused by construction, maintenance and disposing of rolling stock is also calculated. Emission caused by operation are calculated based on rolling stock, passenger numbers, load factors and electricity mix for every line. They are also expressed in relation to passenger kilometers (ibid.:29) and can be seen in Table 8. The difference in emissions from the construction phase mostly results from the higher share of viaducts on the east Asian lines (ibid.:25). The lower carbon intensity of HSR operation in France results from the low carbon intensity of the French electricity mix (ibid.:29ff.).

Table 8: Carbon intensities of four HSR lines (Baron et al., 2011:30)

Emissions [gCO2/pkm]	Atlantic	Mediterrean	Taipei-Kaohsiung	Beijing-Tianjin
Construction	3.7	4.3	8.9	6.0
Rolling Stock	0.9	1.0	0.9	0.8
Operation	5.7	5.7	42.9	39.2
Sum	10.3	11.0	52.7	46.0

Baron et al. (2011) also perform a more detailed analysis on mode shift and net environmental benefit of HSR on the Valence-Marseille corridor on the Mediterrean line. They calculate carbon intensities for air and road transport of 163.2 and 130.0 gCO2/pkm, respectively, applying a similar comprehensive approach as for the four HSR lines.

One can interpret the carbon intensity of the Atlantic HSR line as a soft lower bound for HSR overall, because construction of this line involved only a small share of tunnels and bridges and the French electricity mix is relatively climate-friendly. Similarly, the Taiwanese line from Taipei to Kaohsiung can pose as an upper bound, due to its high share of tunnels and bridges and the high carbon intensity of the Taiwanese electricity mix. All four lines however attract a relatively high number of passengers (20 million, 20 million, 32 million and 25 million per year (ibid.:19ff.)) compared to other lines in the literature corpus, partially explaining the advantageous emissions per passenger kilometer compared to alternative modes on all lines. It is worth to note that the study was produced for the UIC, which has an interest in promoting HSR as an environmentally friendly transportation system.

While Baron et al. (2011) added emissions from construction and operation to calculate the overall carbon intensity of HRS lines, Bueno et al. (2017) take a different approach. They too perform a LCA for a HSR line, namely the planned "Basque Y" in Basque country, Spain. They also calculate total embodied carbon emissions and carbon intensity from operation. However, instead of adding them together, the authors calculate the time needed for a forecasted mode shift from air and road transport to HSR to offset the initial emissions from the project's construction. Bueno et al. (2017) consider the phases of construction and maintenance and calculate total emission due to infrastructure provision of 45,187 tCO2/year. Tunneling alone accounts for 30,780 tCO2/year, since the route traverses challenging terrain (ibid.:4). Based on a total route length of 180 km, 108 km of which is underground (ibid.:4), this translates to 251.0 tCO2/km, year for the whole route and 285.0 tCO2/km, year for tunnel sections. However, these estimates are based on lifetimes of only 60 years for major infrastructure components (ibid.:4), compared to 100 years assumed by Baron 2011. Based on data from the Basque government, the authors estimate the carbon intensity of the operation of HSR at 32, of coach at 28, of CR at 45, of air transport at 127 and of car at 138 gCO2/pkm. The passenger forecast for the Basque Y is relatively low, at around 5 million passengers a year equivalent to 2.45 million trips across the

whole route length (ibid.:6). Facing imminent threats from climate change, the authors also remark that "[...] present emissions have more negative climatic impact [sic] than future ones [...]" (ibid.:10), advocating for the use of carbon discounting rates.

Chester & Horvath (2010) choose yet another approach to comparing embodied emissions to emission (savings) from HSR operation. Based on the Ecoinvent 1.3 database they carry out a LCA of CAHSR, including resulting emissions from infrastructure, vehicle and electricity production (ibid.:2). They then normalize total emissions against the forecasted 35 million rail vehicle kilometers per year as a fixed base (ibid.:4). Carbon intensities are expressed in CO2eq per passenger kilometer for HSR, CR, car and air transport as a function of each mode's load factor. This allows the authors to calculate break-even points between modes depending on the number of passengers per vehicle. Figure 7 demonstrates this relationship. For example, for HSR to break even with a fully seated airplane (120 seats filled resulting in 100 gCO2/pkm), the train would need to seat 873 passengers (translating to a load factor of 72 %). The carbon intensity of HSR in this model can vary between 75 and 750 gCO2eq/pkm (assuming 1200 or 120 passengers per train, respectively) (ibid.:5). Assuming the occupancy rate of the CAHSR authority's forecast of 63 % or 761 passengers per train (ibid.:4) this translates to 118 gCO2eq/pkm. This is more than in most other sources studied. An unusually large share of the project's CO2eq emissions are attributed to active vehicle operation (ibid.:5). This discrepancy is discussed at the end of this chapter.

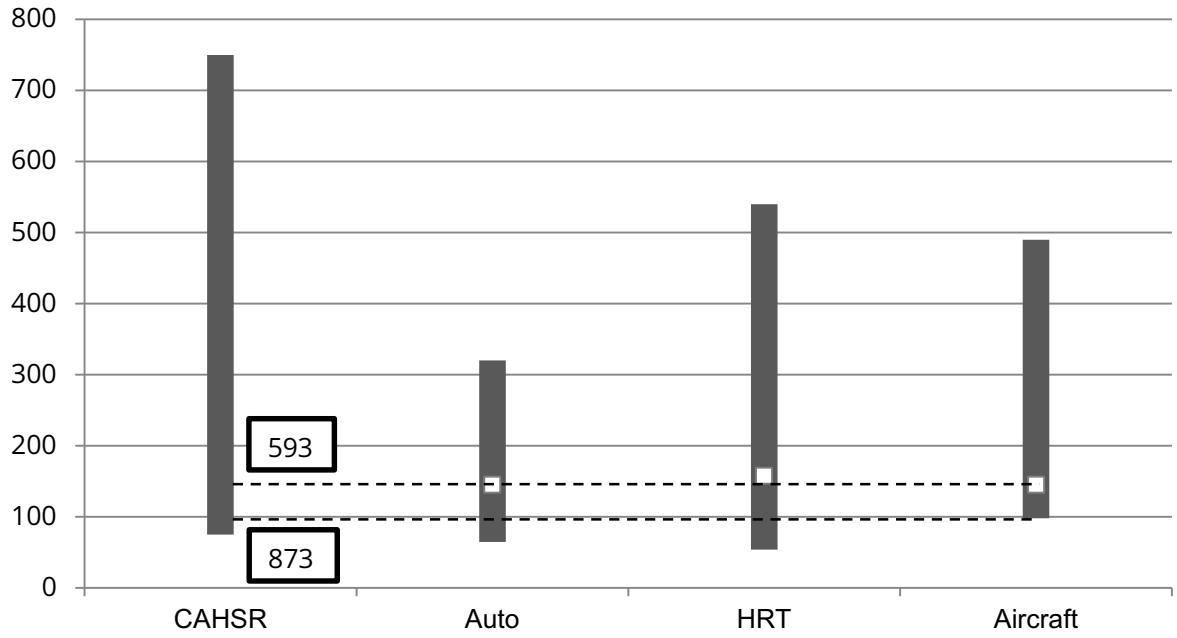

Figure 7: Carbon intensities [gCO2/pkm] for different modes and load factors on the Los-Angeles – San Francisco corridor. Passengers per vehicle: HSR: 120-1200, auto: 1-5, HRT: 35-350, aircraft: 24-120. Central estimates (based on 2.2, 120 and 81 passengers per vehicle) marked as white squares (Chester & Horvath, 2010:6)

Jehanno et al. (2011) put forward a report about the environmental impacts of HSR. Like Baron et al. (2011), this report is sponsored by the UIC. The authors calculate average carbon intensities for operation of HSR, coach, car and air traffic in Europe to be 17, 30, 115 and 153 gCO2/pkm, respectively (ibid.:16). For HSR infrastructure, the authors estimate embodied emissions in the range of 58 - 176 tCO2/km, year or 3.7 - 8.9 gCO2/pkm (ibid.:18).

Jones et al. (2016) carry out an ex-ante LCA for a 297 km long, planned HSR from Lisbon to Porto. They estimate that over the line's life cycle, 684 ktCO2eq would be emitted, 68.6 % of which is attributed to train operation and only 1.9 % to track construction (ibid.:10). Carbon intensity is calculated to be 13.7 gCO2eq/pkm (ibid.:11). It is important to note that while track construction is included in the scope of the LCA, construction of tunnels and aerial structures is not (ibid.:7). Since one can expect the line to require such construction due to the demanding topography and the resulting emissions are higher than those from operation in several studies, I only include this study's findings regarding carbon intensity of operation, which is 9.4 gCO2eq/pkm. The authors point out the high sensitivity of their results to the underlying electricity mix (ibid.:12ff.).

Kommalapati et al. (2019) perform a LCA on a proposed HSR line between Houston and Dallas along the I-45 corridor. To calculate total CO2eq emissions of the HSR system, they include resource extraction and transport, construction, operation, maintenance and end of life for both infrastructure and vehicles (ibid.:9). The authors use emission factors from the Ecoinvent v3 database (ibid.:14). A similar yet simplified approach is used to calculate carbon intensity of air and road transport along the corridor (ibid.:9). Based on forecasts of 6.2 million passengers per year on 24,820 one way vehicle trips (ibid.:15) and an infrastructure lifetime of 60 years (ibid.:18), GHG emissions are estimated at 14.5 kgCO2eq/pkm [sic] for the vehicle component and 41.84 kgCO2eq/pkm [sic] for the infrastructure component. 56.76 % of these emissions are attributed to the construction phase of infrastructure (ibid.:26). Comparing these figures to intermediate calculations throughout the study, I conclude that the authors mean gCO2eq/pkm instead of kgCO2eq/pkm, and include them as such in the overview. The 23.75 gCO2eq/pkm attributed to infrastructure construction appear high compared to other sources, considering the I-45 corridor would involve few tunnels and bridges and provides an existing right of way.

In a fashion similar to Chester & Horvath (2010), Kommalapati et al. (2019) vary the passenger numbers with all other factors staying constant to express carbon intensity as a function of the occupancy rate. Assuming carbon intensities of 110, 130 and 270 gCO2eq/pkm for coach, aircraft and car respectively (ibid.:22), they demonstrate that HSR breaks even with all of these modes at less than 33 % occupancy rate. Figure 8 illustrates this relationship.

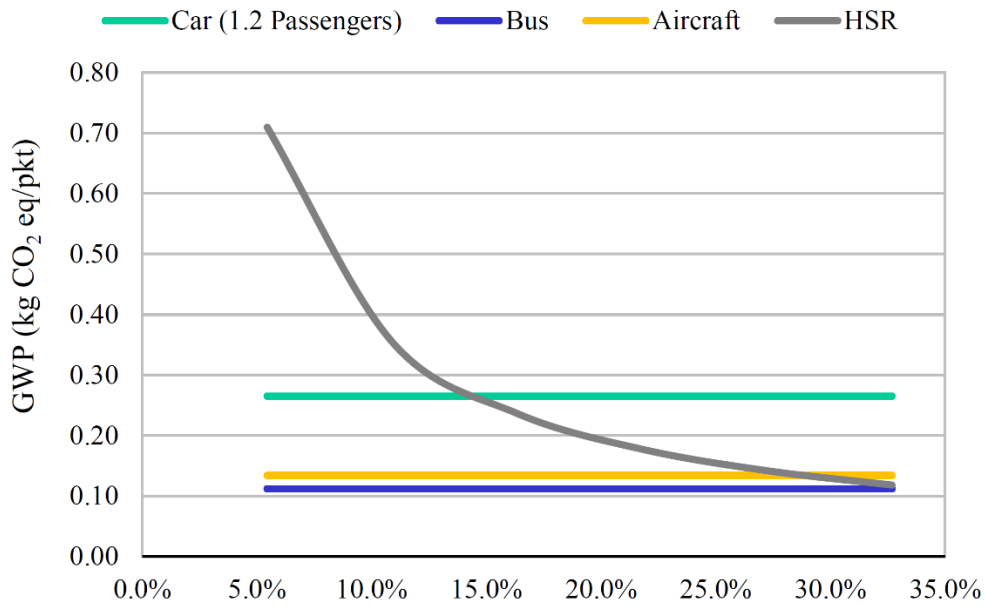

Figure 8: Carbon intensity of HSR and alternative modes as a function of HSR occupancy rate (Kommalapati et al., 2019:22)

Miyoshi & Givoni (2013) carry out a LCA for HS2, a HSR line under construction between London and Manchester. They base their calculation on average emission intensities for at-grade, tunnel or viaduct sections (ibid.:114) and demand forecasts by the Department for Transport, which assumes 16.2 million passengers in the starting year and 35 million passenger in 2033 (ibid.:113f.). The authors estimate that the operation of rolling stock during the first 40 years of operation causes average emissions of 18.3 gCO2/pkm. Operation support is calculated to cause 5.1 and infrastructure construction and maintenance 3.2 gCO2/pkm. Total carbon intensity is estimated at 26.6 gCO2/pkm (ibid:118). The authors attest that this value is low compared to other countries due to the high ridership estimates for HS2 (ibid.:118). To estimate the total reduction in GHG emissions due to the project, the authors assume carbon intensities of 210 and 160 gCO2/pkm for air and road transport (ibid.:118).

Westin & Kageson (2012) construct a general GHG emission model for HSR. In this model, they vary the carbon intensity of electricity production, occupancy rates, how much demand is shifted from which modes to HSR and several other parameters, using the Monte Carlo method, to calculate distributions of the minimal ridership necessary to offset embedded emissions. Based on estimates from Network rail and assuming a share of tunneling of 10 % of total route length, the authors calculate GHG emissions due to construction of 118 ktCO2eq/year for a 500 km route (ibid.:5), which translates to 236 tCO2eq/km, year. Assuming the most optimistic and pessimistic parameter values provided by the authors (ibid.:3), I calculate a range of 6.9 to 35.5 gCO2/pkm (electricity consumption of trains only). For air transport, coaches and private cars, the same method yields carbon intensities of 62 – 151, 14 – 32 and 32 - 82 gCO2/pkm, respectively.

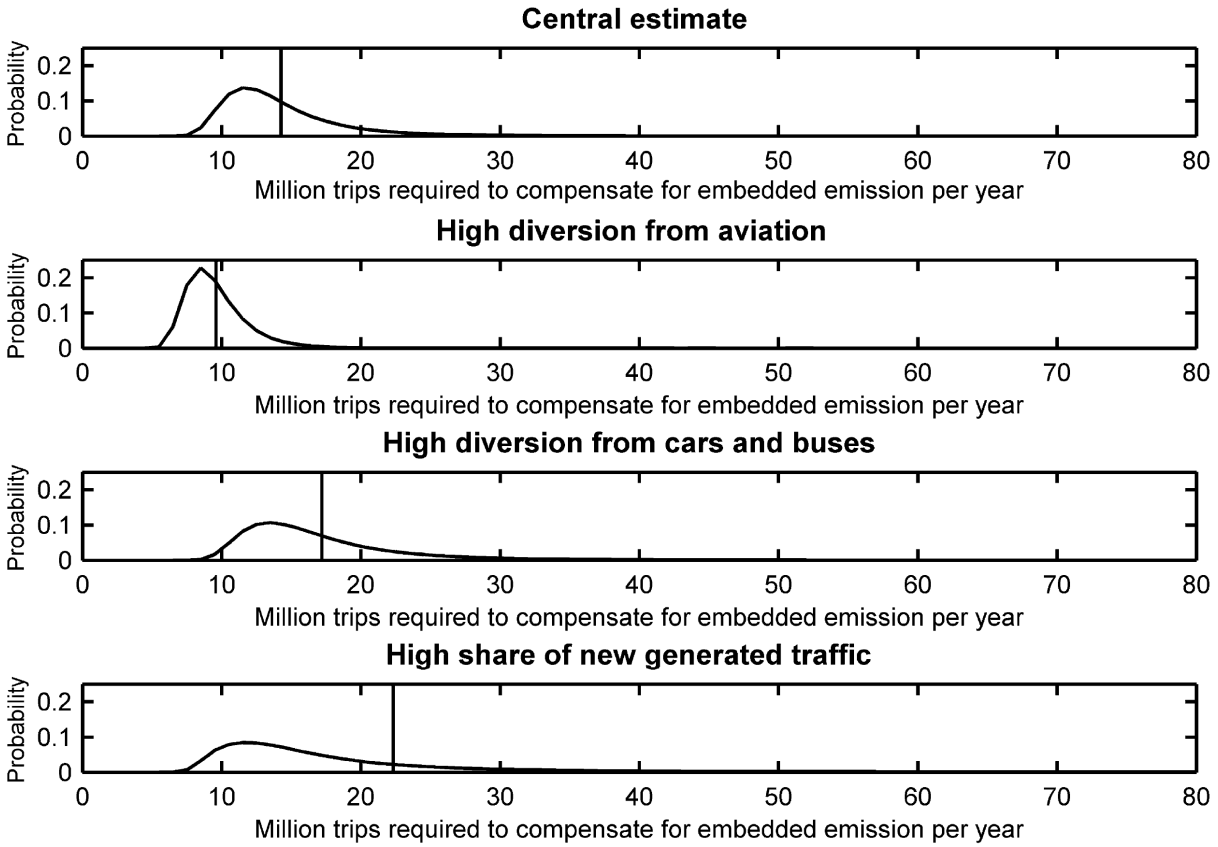

Figure 9: Distributions of annual passenger numbers needed to compensate for the embedded emissions from construction of the HSR line (Westin & Kageson, 2012:5, cropped)

4.3.4 Methodological Remarks

GWP is usually expressed in terms of kg of CO2 or CO2eq. Baron et al. (2011:4) argue that since CO2 emissions of rail and road account for more than 90 % of those modes' GWP, only looking at CO2 emissions instead of CO2eq would "[...] not result in a systematic fault in the carbon footprint calculation". As this literature review demonstrates, both CO2 and CO2eq are used in estimating the GWP of HSR. It falls outside of the scope of this paper to adjust values from studies calculating CO2 emissions to represent CO2eq, due to a large number of different methodological approaches among the sources. Following the judgment of Baron et al. (2011) and other sources, I assume differences in carbon intensity of HSR measured in CO2 and CO2eq to be small enough to be able to compare the different values alongside each other.

This simplification does not apply to air transport however. The GWP of emissions from air traffic is higher than that of emissions emitted in lower atmospheric layers. This is because aircraft emissions have specific effects in the higher atmosphere, such as ozone formation, methane degradation, stratospheric water, contrails and aerosols (Jungbluth & Meili, 2018:1). Accordingly,

the impact of air transport on climate change would be underestimated if compared to emissions from other modes solely in terms of mass of emitted GHG. The higher GWP of air traffic emissions compared to ground transport is expressed by the radiative-forcing-index (RFI). The RFI is multiplied with the GWP of air transport expressed in CO2eq to attain values expressed in CO2eq at ground level. This factor varies for different atmospheric layers, strictly speaking making it necessary to calculate unique RFI factors for every flight profile (Givoni, 2007:213f.). In practice however, average values are used. Jungbluth & Meili (2018) advise to apply a RFI of 1.7 to all CO2 emissions from aircrafts (ibid.:6) to calculate the GWP of air transport. Of the studies analyzed in this chapter, only DG MOVE (2014), Givoni (2007) and Westin & Kageson (2012) include the RFI in their comparisons of air transport and HSR. Givoni (2007) does not apply a RFI to overall emissions, but differentiates NOx emissions by altitude of emission before converting to CO2eq (ibid.:220,222), resulting in a RFI of roughly 2 for the flight from London to Paris (based on figures of ibid.:222). Westin & Kageson (2012) apply a RFI of 1.0 – 1.5 to overall air transport emissions.

To include the higher GWP of air transport compared to HSR, I multiply the obtained values for carbon intensity of air transport operation from sources that disregard this effect with a RFI of 1.7 in Table 11. However, I do not further differentiate between sources declaring GHG emissions of air transport in CO2 or CO2eq, as this falls outside of the scope of this research paper for the same reasons as mentioned earlier.

While the discrepancies in embedded emissions among the sources can be explained by methodological differences (such as different scopes of the LCA) and different route characteristics, I find an inexplicable discrepancy regarding train operation. Prompted by the comparatively high emissions from train operation found by Chester & Horvath (2010), I investigate the available supplementary data. The assumed energy consumption of trains does not match up with values found in other sources, even acknowledging there being a large variance among all sources examined. Chester & Horvath (2010:S2) assume an energy consumption of 170 kWh/vkm for trains with a capacity of 1200 seats. Baron et al. (2011:29) assume a uniform 24.1 kWh/vkm for trains offering 385 to 526 seats. Both sources claim to take the German ICE trains as a reference source. Alvarez (2010:29) calculate an electricity consumption of 0.073 kWh/pkm for HSR in Spain. Assuming a load factor of 0.7 (ibid.:33) and 1200 seats per train (as assumed by Chester & Horvath, 2010), this translates to 61.32 kWh/vkm. Dalkic et al. (2017:17) report electricity consumptions of 10.4 and 11.05 kWh/vkm for trains providing 409 seats. Prussi & Lonza (2018:5) assume an electricity consumption of 0.037 kWh/seatkm, which translates to 44.4 kWh/vkm for trains offering 1200 seats. Westin & Kageson (2012:3) assume an energy consumption of 0.026 - 0.033 kWh/seatkm, translating to 31.2 - 39.6 kWh/vkm for trains offering 1200 seats. In a study not included in the literature corpus, Fritz et al. (2018) calculate specific energy consumptions of trains. For a typical system speed between 300 and 330 km/h they reach values of 40 - 70 Wh/pkm (ibid.:153), which, again assuming a load factor of 0.7 and a 1200 seat train, translates to 48 - 84 kWh/vkm.

Table 9: Energy consumption of HSR trains normalized to 1200 seats/train

Source	kWh/vkm
Chester & Horvath (2010)	170
Baron et al. (2011)	63
Alvarez (2010)	61
Dalkic et al. (2017)	32
Prussi & Lonza (2018)	44
Westin & Kageson (2012)	31 - 40
Fritz et al. (2018)	48 - 84

The divergence of Chester & Horvath (2010) from the other sources cannot be explained by CAHSR operation patterns, since the route does not involve particularly frequent stops, or by other route characteristics. I therefore exclude the carbon intensity of train operation found by Chester & Horvath (2010) from the interim conclusions.

4.3.5 Interim Conclusions

Table 10 and Table 11 summarize the findings from the literature corpus about the carbon intensity of HSR construction and operation as well as alternative modes. I convert some values from their original units in the source material to allow for an easier comparison.

In the literature, carbon intensity of HSR varies between 10 and 283 gCO2/pkm. This wide range arises from different embodied emissions in infrastructure, different carbon intensities of operation and different ridership numbers. The carbon intensity of infrastructure construction mainly depends on the share of tunnel and bridge sections. This finding is especially relevant for HSR projects in East Asia, where even in topographically less challenging terrain large portions of routes are constructed on elevated structures. Especially in cases where embodied emissions are large compared to those from operation, high ridership numbers are essential to reduce the carbon intensity in terms of CO2/pkm. The carbon intensity of operation mainly depends on the carbon intensity of the respective country's electricity mix. Emissions from the construction of rolling stock are small compared to those from construction of infrastructure and operation. It is not expedient to calculate an average carbon intensity for HSR as a transportation system, since emissions will drastically vary from project to project. Carbon intensity and consequent environmental benefits need to be evaluated in the specific context of a project. This is also relevant because the findings show that HSR can, under unfavorable conditions, exhibit higher carbon intensities than alternative modes such as air transport.

Some sources include evidence that a decline in demand in alternative modes from mode shift might slightly increase these modes' carbon intensity. For example, as demand for air transport is reduced, the average size of airplanes used on that route decreases (D'Alfonso et al., 2015:128), resulting in higher emissions per passenger kilometer. However, this impact is not included in any study that quantifies the environmental impact of HSR. Within the scope of this paper I consider this impact to be negligible, since the size of a plane would need to change considerably to result in relevant changes in carbon intensity. The small differences between the reduction of flight frequency and seats provided found by Zhenhua Chen (2017) demonstrate that HSR introduction reduces aircraft size only marginally.

Regarding further research need one can attest that carbon intensities of HSR and alternative modes are generally well studied. The high variance of such values between different studies can mostly be explained by factual differences between the examined cases. However, the impact of tunnels and aerial structures on the overall carbon intensity of HSR infrastructure construction should be studied more closely. I find consistent evidence that one kilometer of tunnel or bridge construction results in CO2 emissions that are by an order of magnitude larger than those of at-grade sections. Considering that the amount of tunnel and bridge sections is the most important factor in determining the embodied emissions in HSR infrastructure, concrete values for this relation are too rare and inconclusive

Table 10: Summary of carbon intensity values of HSR

Base source	Operation of trains	Construction of infrastructure		Total	Notes
	[gCO2eq/pkm]	[tCO2eq/km, year]	[gCO2eq/pkm]	[gCO2eq/pkm]	
Alvarez (2010)	27				
D'Alfonso et al. (2016)	64				
Givoni (2007)	30				
Dalkic et al. (2017)	17 - 18				Case studies
	4 - 33				Literature review
Prussi & Lonza (2018)	15 - 34				
Robertson (2013)	50				
Chang & Kendall (2011)		33			
Cheng et al. (2020)		230			Aerial structures only
de Bortoli et al. (2020)		2.8 - 5.5			
Lin et al. (2020)		288			
Olugbenga et al. (2019)		0.13 - 169			Literature review
		1.0			Average at-grade equivalent
		37			Average tunnel sections
Baron et al. (2011)	6 - 43	58 - 177	3.7 - 8.9	10 - 53	Lower/upper bound: France/Taiwan
Jehanno et al. (2011)	17	58 - 177	3.7 - 8.9	21 - 26	Partially referencing Baron 2011
Bueno et al. (2017)	32	251	103	283	Lifetime: 60 years
		285			Tunnel sections only. Lifetime: 60 years
Jones et al. (2016)	9.4				
Kommalapati et al. (2019)	15		24	39	Lifetime: 60 years
Miyoshi & Givoni (2013)	18	205	3.2	27	Lifetime: 40 years
Westin & Kageson (2012)	6.9 - 36	236		242 - 272	Monte Carlo simulation
CO2 assumed as CO2eq. Lifetime of infrastructure assumed 100 years unless indicated otherwise. Values smaller than 100 rounded off to two significant digits.					

Table 11: Summary of carbon intensity values of alternative modes

Base source	Carbon intensity [gCO2eq/pkm]				Notes
	Air	private car	coach	CR	
Alvarez (2010)	287	113	32	38	
D'Alfonso et al. (2016)	780				London-Paris
DG MOVE (2014)	133 - 247				Based on ibid.:60
Givoni (2007)	321				London-Paris
Dalkic et al. (2017)	170 - 286	104 - 116		50 - 60	
Prussi & Lonza (2018)	189 - 243				7 intra-EU routes
Robertson (2013)	153				Sydney-Melbourne
Baron et al. (2011)	277	130			Valence-Marseille
Bueno et al. (2017)	216	138	28	45	
Chester & Horvath (2010)	247	145		155	Los Angeles - San Francisco
Jehanno et al. (2011)	260	115	30		
Kommalapati et al. (2019)	221	270	110		Houston-Dallas, car and coach incl. highway infrastructure
Miyoshi & Givoni (2013)	357	160			
Westin & Kageson (2012)	62 - 151	32 - 82	14 - 32	5 - 28	

CO2 assumed as CO2eq for modes other than air. RFF of 1.7 applied to all sources other than DG MOVE (2014), Givoni (2007) and Westin (2012). Only operation unless indicated otherwise. Rounded off to full gCO2eq/pkm.

4.4 FIELD 3: MODE SHIFT TO HSR

For HSR to cause an overall reduction in GHG emissions, not only must its carbon intensity be lower than that of alternative modes, but there must also occur a mode shift from these more carbon intense modes to HSR. In this chapter, I summarize findings from the literature corpus about the extent of such mode shifts. First, findings from theoretical models are analyzed. Then, I look at ex-ante projections of mode shift for specific HSR projects. In the third subchapter, ex-post evaluations of realized projects are examined. Finally, I summarize findings of regression studies that analyze data from transportation markets affected by multiple realized HSR projects. At the end of this chapter, I present likely value ranges for mode shift from air transport, road, coach and CR to HSR.

4.4.1 Theoretical Models

D'Alfonso et al. (2015) build a duopoly model for economic competition between HSR and air transport. In their model, both HSR and air transport operators try to maximize their profits by varying the amount of seats supplied on their mode and service frequency. The HSR operator can also vary speed (ibid.:119). The authors prove that, within their model specifications, the introduction of HSR leads to a reduction of air traffic (ibid.:123). However, the authors do not provide concrete values.

Jiang & Zhang (2014) build an economic model focused on the effects of competition and cooperation between hub-and-spoke airlines and HSR at capacity-constrained airports. They find that cooperation (such as code sharing) reduces air traffic on HSR accessible markets (ibid.:46).

In a general GHG emission model for HSR, Westin & Kageson (2012) assume ranges for the share of HSR traffic that is diverted from alternative modes. The authors assume that 12 - 32 % of HSR traffic is shifted from air transport, 14 - 32 % from car and 20 - 40 % from CR (ibid.:3). These upper and lower bounds are values that the authors deem "to provide estimates that significantly differ from the central value without being completely unrealistic" (ibid.:2). In comparison to the empirical data from Givoni & Dobruszkes (2013), these ranges appear small.

4.4.2 Ex-Ante Project Demand Evaluations

Bueno et al.'s (2017) calculations of the net environmental impact of the planned „Basque Y" HSR project are based on official passenger number forecasts produced by Adif (2009). I am unable to retrieve the primary source. The demand estimates in Table 12 are therefore displayed as reported by Bueno et al. (2017).

Table 12: Mode shift projections for the "Basque Y" (Bueno et al., 2017:6)

Mode	Car	Coach	CR	Air transport
Shifted transport to HSR [Mpkm/year]	229.6	66.4	56.4	37.5
Share of HSR demand [%]	52.1	15.1	12.8	8.5

Matute et al. (2015) calculate that once completed, 17 % of passengers on CAHSR would have used air transport and that 81 % would have used their private car instead of traveling by HSR. These estimates are based on figures from cost-benefit-analyses on the project (ibid.:107).

Miyoshi & Givoni (2013) estimate demand for the HS2 project from London to Manchester based on data from the official project appraisal. For the year 2033, they estimate 94,800 passengers per day, 70.4 % of which will come from CR, 4.2 % from road transport, and 2.8 % from air transport (ibid.:113).

In all three cases, the authors do not provide information about the present level of car, coach, CR or air traffic inside the area of investigation, so these mode shifts cannot be expressed relative to the transportation levels of the incumbent modes.

4.4.3 Ex-Post Project Demand Evaluations

Baron et al. (2011) report travel demand data from RFF & SNCF (2007) for the Valence-Marseille LGV-line. According to the primary source, the number of rail passengers between the two cities increased from 15.9 before to 20.4 million passengers per year after the opening of the new HSR line (ibid.:9). It reports that of those additional 4.5 million passengers per year, 40 % would have flown and 27 % would have taken the car (ibid.:75). Including the 15.9 million passengers a year that would have taken CR instead, I calculate that 78 %, 9 % and 6 % of HSR demand stems from CR, air transport and private car traffic respectively.

Dalkic et al. (2017:16f.) perform a SP survey among 421 HSR users to estimate ridership distribution in a non-HSR scenario. They find that on the Ankara-Eskisehir/Ankara-Konya routes, 13/27 % would have used a private car, 81/68 % would have travelled by coach and 3/3 % would have taken CR (ibid.:18). The authors note that there were no air transport services available along the corridors before or after HSR introduction (ibid.:5).

Dobruszkes (2011) compares the development of HSR and air transport market shares on five European flight routes before and after the introduction of HSR. He finds that new HSR links can be accompanied by a reduction in air passenger numbers and flight frequency, however only so on routes where HSR is very competitive in terms of travel time (such as Paris-Brussels at 80 min) (ibid.:874). Overall, the introduction of HSR has not managed to stop the growth of the aviation industry, especially on medium distances and due to the introduction of LCC airlines (ibid.:878f.).

Givoni & Dobruszkes (2013) carry out a meta-study of ex-post demand evaluations for HSR services. Table 13 shows the range of values for mode shifts across the case studies, measured as a share of HSR demand. They also gather data about changes in the level of ridership on alternative modes due to the introduction of HSR (ibid.:733f.). Both data sets are included in Table 17 and Table 18.

Table 13: Ex-post mode shift data for HSR projects, extreme values underlined (Givoni & Dobruszkes, 2013:729)

Route	Origin of HSR demand as a percentage of total HSR demand [%]			
	CR	Air	Car	Coach
Paris-Brussels-Cologne/Amsterdam	47	8	31	3
London-Paris/Lille/Brussels	12	49	7	12
Paris-South-east		33	18	
Madrid-Seville (1994)	14	32	25	3
Madrid-Seville (1996)	18	42	20	5
Rome-Naples	69	<1	8	<1
Osaka-Hakata	55	23	16	
Korea (first stage)	56	17	12	
Wuhan-Guangzhou	50	5		15

The figures demonstrate that route characteristics (i.e. length and incumbent transportation systems) determine from which modes HSR obtains its demand. Routes with geographical constraints that have a high share of air traffic prior to HSR experience a strong decline in air traffic after HSR introduction (e.g. London-Paris/Lille/Brussels across the English Channel). Routes that are short enough for CR to compete with air traffic prior to HSR experience a strong mode shift from CR to HSR (e.g. Rome-Naples).

Lopez Pita et al. (2012) examine the special competitive situation of HSR and air transport on the Madrid-Barcelona route. Prior to the introduction of HSR in February 2008, this city pair had the highest volume of air traffic in Europe, at 4.8 million passengers in 2007 (ibid.:129). Even though the AVE cut travel time by HSR from 5 ½ hours to 2 ½ hours, air traffic only fell from 4.8 to 3.6 million passengers per year. While air transport lost 1.2, CR and HSR gained a combined 1.3 million passengers per year, resulting in a total of 2.1 million passengers per year on CR and HSR (ibid.:125). Assuming all rail passengers between Madrid and Barcelona and all previous air passengers use HSR, this translates to 57 % of HSR demand coming from air transport and 38 % from CR. The authors attribute the high number of air passengers after the introduction of HSR to the remaining attractiveness of air transport due to high flight frequency and low prices (ibid.:.129).

4.4.4 Regression Studies

Givoni & Dobruszkes (2013) compile ex-post HSR and air transport market shares for 24 city pairs. While technically not carrying out a complete regression analysis, the data illustrates the general relationship between HSR travel time and HSR market share, demonstrating that HSR is more

competitive against air transport on shorter routes with low travel times. As the findings from the other sources examined in this chapter emphasize however, the mode share of HSR cannot be equated to its mode shift impact.

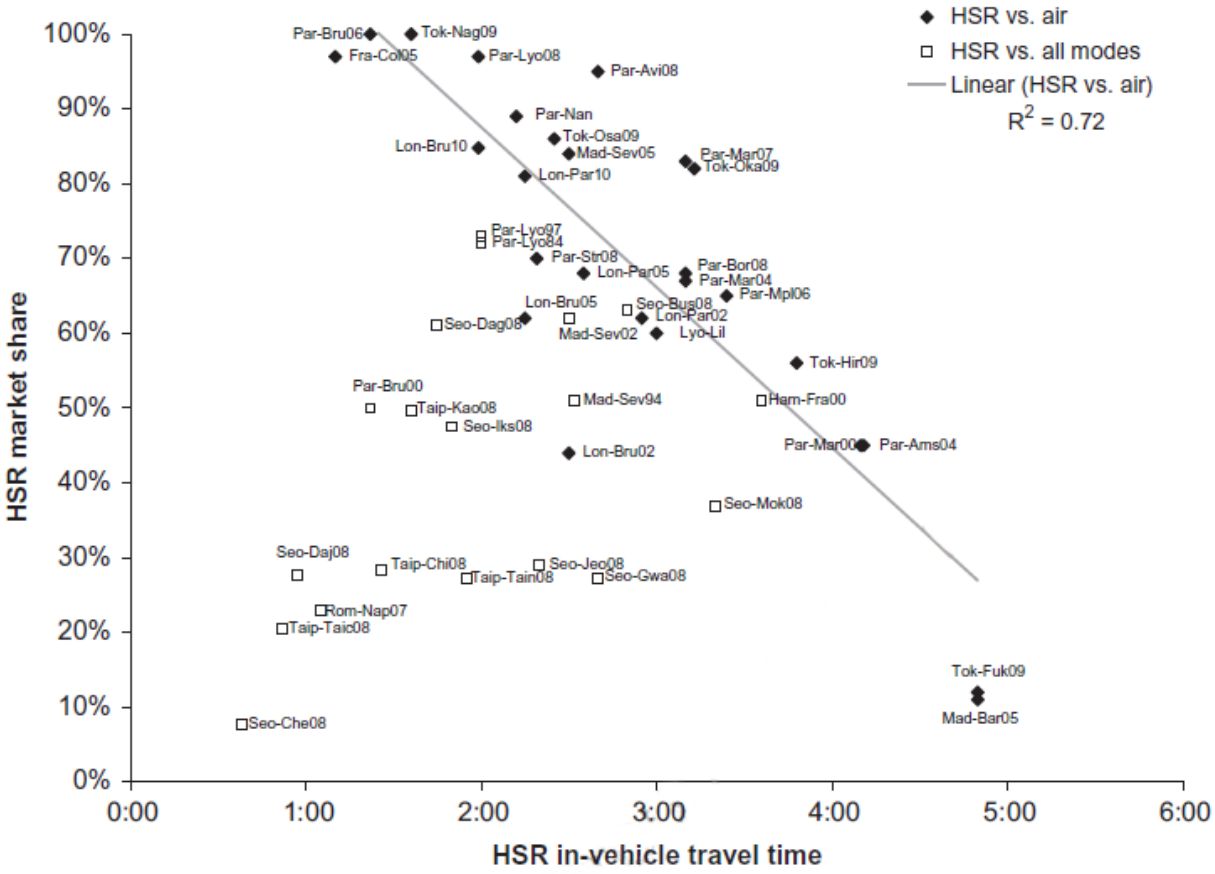

Figure 10: Relationship between HSR in-vehicle travel time and HSR market share (Givoni & Dobruszkes, 2013:180)

Cascetta & Coppola (2015) conduct RP and SP surveys and analyze passenger and traffic count data from HSR, CR, highways and domestic air transport in Italy. They use data from 2009 to 2013, a time where new HSR lines were opened and new HSR operators entered the market on existing routes, increasing competition among HSR operators and lowering fares (ibid.:9). They find that in the HSR accessible parts of Italy, mode shares of highway, air transport and CR fell, while that of HSR rose. Their figures are presented in Table 14. They estimate that of the 13.8 million yearly HSR trips added between 2009 and 2013, 2.5 million stem from CR, 2.3 million from air transport and 3.5 million from private cars (ibid.:14), translating to 18, 17 and 25 % of added HSR demand respectively. These figures do not allow to draw conclusions on HSR induced mode shift however; due to an economic crisis, overall number of trips in the long-distance market fell (ibid.:12), and

mode share does not take into account average trip lengths, which is relevant for the environmental impact.

Table 14: Mode share in Italian long-distance market (Cascetta & Coppola, 2015:13)

Mode	Mode share by year [%]	
	2009	2013
Highway	57.3	45.2
Air transport	10.5	7.3
CR	7.0	3.2
HSR	25.2	44.3

Castillo-Manzano et al. (2015) aim to measure the substitution effect between HSR and air transport in Spain, using an intertemporal regression analysis. The authors choose the monthly number of domestic passengers at Madrid Barajas airport as the endogenous variable, because in 2011 84 % of Spanish HSR passengers came from or were bound for Madrid. As exogenous variables, they choose the number of domestic air operations at Madrid Barajas, HSR passenger numbers, the population of provinces connected by HSR, and the unemployment rate in the province of Madrid. Exogenous dummy variables are introduced for a snowfall event in 2009, the number of business days per month, and for monthly seasonality effects (ibid.:61). They find that, from 1999-2012, on average only 13.9 % of HSR passenger demand came from air transport. Several ex-ante estimations assumed higher substitution rates (ibid.:63).

Clewlow et al. (2014) and Dobruszkes et al. (2014) carry out panel regression analyses on European city pairs, yielding consistent results. Clewlow et al. (2014:138) use data about 35 airports and 90 airport pairs in France, Germany, Italy, Spain and the UK from 1995 - 2009. Endogenous variables are price of jet fuel, GDP, population, population density and rail in-vehicle travel time. Exogenous dummies are hub status and presence of LCC. Clewlow et al. (2014:139) create four models: city-to-city, airport-to-airport, domestic air traffic at an airport and intra-EU air traffic at an airport. The exogenous variable is the air traffic passenger count per year on each route or at each airport, depending on the model. Dobruszkes et al. (2014) use data from 161 city pairs. They constructs two models that use the number of seats and the number of flights offered by airlines as endogenous variables. Exogenous variables are population and population ratio between origin and destination. Exogenous dummies are countries, hub status of the origin or destination airport and whether HSR services call at central or peripheral stations at the origin or destination city.

Clewlow et al. (2014) find that the introduction of HSR decreases domestic air traffic at airports by 12.3 %, but only by 0.9 % and 2.3 % for intra-EU and total traffic. In this context however, the introduction of HSR only means that the airport is accessible by HSR, not that the respective air

service competes with HSR (ibid.:142). HSR travel time between airports or cities is more relevant for changes in air traffic on the respective routes. The logarithmic elasticity of air traffic against changes in HSR travel time is 4.734 for city pairs and 5.261 for airport pairs. The authors remark however that these values are likely distorted by a small number of outlier relations in the dataset where air travel ceased altogether (ibid.:140f.). Dobruszkes et al. (2014) find a logarithmic elasticity of airline seats offered against changes in HSR in-vehicle travel time of 1.094 - 4.380. The logarithmic elasticity of the number of flights offered against changes in HSR in-vehicle travel time is 0.915 - 2.375 (ibid.:470). One needs to take into account that Dobruszkes et al.'s (2014) elasticity range is for airline seats while Clewlow et al. (2014) look at passenger numbers, which one can expect to be more elastic than seat numbers, and that Clewlow et al.'s (2014) values are slightly distorted upwards. Considering this, I find that Dobruszkes et al.'s (2014) value range for logarithmic elasticities of airline seats offered (which is more relevant to the environmental impact than passenger numbers) against changes in HSR in-vehicle travel time of about 1.1 - 4.4 appears plausible.

C. Chen et al. (2018), Zhenhua Chen (2017), Gu & Wan (2020), Hangjun Yang et al. (2020) and Haoran Yang et al. (2018) perform panel regression analyses on the Chinese aviation market. Table 15 summarizes the data and variables the authors use.

Table 15: Data and variables of five panel regression analyses on the Chinese aviation market

Source	Data	Endogenous Variables	Exogenous Variables
Zhenhua Chen (2017:190)	295 city pairs, 2001-2014, 3834 observations	Air passengers, seats, flights	Population, GCPPC, distance, dummies: hub status, HSR, SARS outbreak, Olympic games, trend
Zhe Chen et al. (2019:91)	394 city pairs, 2011-2017, 10892 observations	Air passengers, flights	Population, GDPPC, distance, dummies: hub status, season, year
Gu & Wan (2020:61f.)	2286 air routes, 2008-2015, 17,888 observations	Seats	HSR travel time, air travel time, HSR frequency, population of feeding cities, population of endpoints, GDPPC, dummies: rail-air travel time difference (category)
Haoran Yang et al. (2018:1)	138 air routes, 2007-2013, 1,890 observations	Air passengers	GDPPC, population, duration of HSR operation, HSR frequency, HSR fare, HSR travel time, ingress and egress time from station, airfare, flight time, ingress and egress time from airport, dummier: HSR, year
Hangjun Yang et al. (2020:4ff.)	280 routes, 2005-2016, 149,368 observations	Airfare, flights	Aircraft size, distance, GDPPC, population, number of carriers, market concentration

Zhenhua Chen (2017) finds that the introduction of HSR leads to the greatest reduction in air transport demand and supply for distances from 500 to 800 km. The corresponding regression results are summarized in Table 16.

Table 16: Impact of HSR introduction on air transport (Zhenhua Chen, 2017:195)

Distance	Reduction of air traffic [%]		
	Passengers	Flights	Seats
< 500 km	18.0 - 20.9	12.7 - 12.9	17.6 - 19.1
500 - 800 km	34.0 - 35.7	24.4 - 25.8	27.0 - 28.8
> 800 km	24.1 - 22.4	23.2 - 24.8	27.7 - 29.2

Zhe Chen et al. (2019:91) find that the introduction of HSR leads to an average reduction of the number of air passengers by 17.0 - 17.9 % and a reduction of the number of flights of 15.0 - 15.8 % (depending on model specification). They too find that the impact of HSR on passenger numbers and flight frequency depends on the travel time distance between air transport and HSR, and therefore also on the distance between origin and destination. They attest a negative power function form relationship. For example, if HSR reduces the difference of in-vehicle time between air transport and HSR from 3 to 2 hours (33 % decrease), air passenger numbers drop by 21.4 %. If the difference is reduced from 5 to 3.3 hours (also a 33 % decrease), air passenger numbers only drop by 15.0 % (ibid.:94ff.).

Gu & Wan (2020:64) find that HSR reduces the number of airline seats offered as long as air travel time is less than 5 hours shorter than that of HSR. Haoran Yang et al. (2018:6) find that the entry of HSR leads to a reduction in the number of air passengers by 27 %. Hangjun Yang et al. (2020:7) find that the number of flights decreases by 44.6 % as HSR is introduced.

Wan et al. (2016) carry out panel regressions on air transportation markets in mainland China, Japan, South Korea and Taiwan. They look at the number of airline seats offered on 467 domestic air routes between 1994 and 2012, resulting in 887 observations (ibid.:535f.). Exogenous variables are population, GDPPC, distance as well as dummy variables for country, HSR and LCC as well as fixed effects for year and route (ibid.:536f.). Wan et al. (2016:542) find that HSR introduction in China and Japan leads to a reduction in the number of air passengers by 83 and 28 % on short-haul and medium-haul routes respectively. They also find that the impact of HSR on air traffic is stronger in China than in the other three countries when accounting for the different route characteristics (namely, longer average distances in China) (ibid.:551).

F. Zhang et al. (2018) also perform two panel regression analyses. For mainland China, Japan, South Korea and Taiwan, air passenger numbers on 1,178 air routes from 2000 to 2014 are considered,

269 of which have direct HSR competition. This results in a total of 10,293 observations. Exogenous variables are population, airport accessibility, GDPPC as well as dummies for HSR, year and the distance category (ibid.:195ff.). The second model considers air passenger traffic at 350 airports situated in the countries above (2000 - 2016) as well as Europe (1997 - 2015). This results in a total of 5,140 observations (ibid.:197). Exogenous variables are population, airport accessibility, GDPPC as well as dummies for HSR, whether the HSR station is integrated with the airport, and year (ibid.:194). F. Zhang et al. (2018:200) find that the introduction of HSR reduces air route traffic the most in Taiwan, followed by South Korea and Japan, due to the different route characteristics. On average, HSR introduction reduces passenger numbers on air routes by 0.8 million, with the impact being more strongly felt on medium-haul and especially short-haul routes (ibid.:203). The authors only provide mean passenger numbers of air routes in their data set (ibid.:194), leaving me unable to calculate the average relative reduction of air passenger numbers.

Liu et al. (2019) put forward a panel regression study on the impact of HSR development on yearly passenger throughput at airports in China and Japan. They use data from 46 Chinese and 16 Japanese airports from 2008 - 2011, resulting in 558 airport-year-observations (ibid.:120). Exogenous variables are the centrality of the city in the HSR network, whether there is a HSR station at the airport, population, GDPPC, and jet fuel price. Dummies are LCC, whether there are competing airports, and year (ibid.:119). The authors find that in China, adding a HSR connection to a city within 500 km on average reduces air passenger numbers at the airport by 267,000 passengers per year. Within 1,000 km, the average reduction is milder at 131,000 passengers per year (ibid:124). Since air passenger numbers are assessed on an airport level but the exogenous HSR variable is route based, I am unable to calculate the relative impact of HSR introduction on air passengers on the competing air route.

4.4.5 Methodological Remarks

I find that the theoretical models examined in this chapter yield no original concrete values for mode shift. Their abstract findings are often contradictory to the findings of empirical works. Several sources point out methodological limitations of regression studies, which make up most of the empirical literature in this chapter. For example, Zhenhua Chen (2017:187) point out that the difference-in-difference approach is not suited for analyzing the impact of HSR, because HSR developments span long periods of time, thus making it difficult to separate exogenous and treatment effects. Suitable data is also more easily available for China where HSR experienced rapid development during the last decade. This leads to a strong regional imbalance among such sources. I find that ex-post case studies provide the richest result in terms of concrete values about mode shifts realized by HSR.

Unlike expected, only few regression analyses actually generated cross elasticities between HSR supply and air transport demand. This is in part due to many sources only including HSR as a binary dummy variable (instead of HSR travel time or generalized travel costs) and because endogenous (air transport) variables were poorly matched with exogenous (HSR) variables. Several sources suggest that fares are an important factor in determining mode shift (Dobruszkes et al., 2014:129; Lopez Pita et al., 2012:466). However, none of the sources analyzed in this chapter generate insights into the role ticket prices play for mode shift and only few include fares at all.

No source from the literature corpus includes mode shift from road transport to CR as an indirect impact of dedicated HSR lines freeing up capacity on CR lines. Especially on congested legacy routes where a large share of HSR demand comes from CR (such as HS2, Italy, or Cologne-Frankfurt), this impact is relevant for the overall environmental impact of the HSR project.

Lastly, I want to point out three different approaches found among the sources analyzed in this chapter for expressing mode shift. One is to regard the difference between an alternative mode's mode share prior to and after the introduction of HSR as a mode shift. For example, if on a given route prior to HSR 60 % and after the introduction of HSR 25 % of travelers use air transport, the difference of 35 percentage points can be interpreted as the mode shift. This approach is not suited for quantifying the net environmental impact of HSR, since it does not allow for easy inference of the difference in the total number of journeys undertaken by air transport.

The second approach I find is to look at the share of HSR journeys that would have been undertaken using an alternative mode in the absence of HSR. Combined with the total number of HSR journeys and carbon intensities, this allows for an easy calculation of avoided emissions, as demonstrated by Bueno et al. (2017) and others.

The third approach is to measure the reduction of an incumbent mode's traffic count relative to its prior level. Such mode shifts can be interpreted as cross-elasticities between alternative modes' demand and HSR supply.

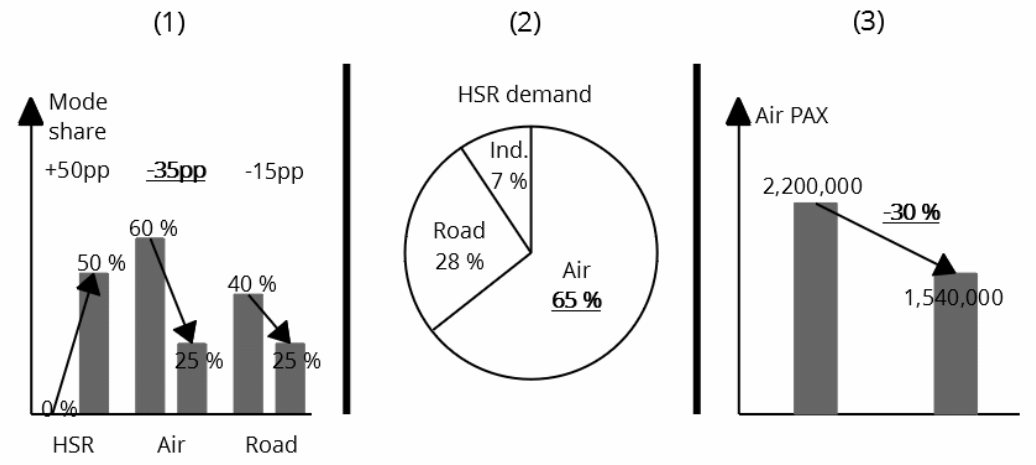

Figure 11: Three different approaches to mode shift calculation (own figure)

On one hand, one can assume that value ranges for mode shifts using the third approach are more uniform for a given mode across similar HSR projects compared to the second approach. This is because mode shifts of a specific mode expressed according to approach three for the most part only depend on characteristics of the route in question and passengers' utility function. Using the second approach, mode shift values for a specific mode would in addition depend on the mode shift from other modes as well as induced demand. On the other hand, to calculate the net change in GHG emissions based on mode shifts expressed according to approach three, one needs to know the respective mode's absolute traffic count prior to HSR. For approach two, only HSR's absolute demand is needed. Such figures might be more readily available. Approach three also might introduce a larger margin of error, since the delimitation between market segments of the alternative mode that do or do not compete with HSR can be challenging. This last point however only applies to sources that regard HSR as a binary dummy variable instead of considering more gradual measures of supply such as travel time.

Considering the different drawbacks and benefits of approaches two and three, I choose to report mode shift according to both in Table 17 and Table 18, respectively. Both types of mode shift data can be used to estimate the overall climate change impact of HSR projects. All sources that report mode shifts according to approach three are regression studies on the impact of HSR on air transport. Due to limited data transparency of the sources I am unable to calculate mode shifts according to approach two for sources that originally provide mode shift values according to method three, and vice versa.

4.4.6 Interim Conclusions

The size and source of a mode shift caused by the introduction of HSR varies from project to project. It is not appropriate to indicate averages of such mode shift values for HSR as a transportation system if they are to be used to evaluate the environmental impact of a specific project. Size and source of mode shift depend on route characteristic such as length, travel time and population, as well as on the incumbent transportation market. Table 17 and Table 18 therefore illustrate plausible ranges of mode shift values, with the specific context of the project being annotated.

I identify several gaps in the research present in the literature corpus. No source includes the benefits of freed up capacity on CR lines due to HSR introduction. This component should be included in future ex-ante projections and ex-post case studies. Due to data availability, empirical studies are largely relating to the Chinese market. Additional research should be carried out to deliver comparable results from the European and other market. Also, most regression analyses only regard the introduction of HSR as a binary dummy variable. To attain more concrete values for cross-elasticities between air transport demand and HSR supply, more differentiated variables

such as HSR travel time or travel time difference should be included. Several studies point out the fares are an important factor in determining mode shifts but fail to address this in their study design. Including fares in empirical mode shift analyses is challenging due to limited data availability, high fluctuations and companies' yield management. Lastly, a systematic review of ex-ante demand projections and ex-post evaluations of HSR projects could substantiate Dobruszkes' (2011:878) claim that ex-ante projections are usually too optimistic.

Table 17: Mode shift values according to method 2: shifted journeys from alternative modes expressed as a ratio of HSR demand

Base Source	Share of HSR demand [%]				Notes
	Air transport	Private car	Coach	CR	
Bueno et al. (2017)	9	52	15	13	Basque Y; short average trip distances, unattractive CR
Matute et al. (2015)	17	81			CAHSR; 725 km LA-SF, strong air and road competition, unattractive CR
Miyoshi & Givoni (2013)	2.8	4.2		70	HS2; LND-BIR/MAN 249/530 km, highly utilized CR
Baron et al. (2011)	9	6		78	LGV Mediterrean; 250 km
Dalkic et al. (2017)		13	81	3	ANK-ESK 277 km, large incumbent coach market
		27	68	3	ANK-KON 306 km, large incumbent coach market
Givoni & Dobruszkes (2013)	8	31	3	47	PAR-AMS/CNG 430/405 km, attractive CR
	49	7	12	12	Channel tunnel; LND-PAR/BRS 342/317 km, no direct CR
	33	18			LGV Sud-Est; PAR-LYN/MRS 432/660 km, high av. travel speed
	42	20	5	18	MAD-SEV (1996) 390 km
	< 1	8	< 1	69	ROM-NPL 189 km, attractive CR
	23	16		55	OSK-HKT 554 km, attractive CR
	5		15	50	WHN-GNZ 968 km
Cascetta & Coppola (2015)	17	25		18	Core area of Italy, 2009-2013
Lopez Pita et al. (2012)	57			38	MAD-BRC 621 km, strong air competition
Westin & Kageson (2012)	12	14		20	assumed ranges (lower bound)
	32	32		40	assumed ranges (upper bound)
Castillo-Manzano et al. (2015)	14				Madrid bound domestic passengers

Rounded off to two significant digits.

Table 18: Mode shift values according to method 3: relative reduction of air traffic as a reaction to HSR introduction

Base source	Reduction of air traffic [%]	Notes
Givoni & Dobruszkes (2013)*	20	PAX Cologne-Munich (621 km)
	22	PAX Madrid-Barcelona (621 km)
	42	Seats Paris-Marseilles (750 km)
	50	PAX Guangzhou-Wuhan (968 km)
	57	PAX Madrid-Seville (470 km)
	80	PAX Taipei-Kaohsiung
	100	PAX Taipei-Chiayi (246 km)
Clewlow et al. (2014)	12	domestic PAX at EU airports
	0.9	intra-EU PAX at EU airports
	2.3	total PAX at EU airports
Zhenhua Chen (2017)**	19	PAX on city pairs < 500 km
	65	PAX on city pairs 500 - 800 km
	24	PAX on city pairs > 800 km
	18	seats on city pairs < 500 km
	28	seats on city pairs 500 - 800 km
	28	seats on city pairs > 800 km
Zhe Chen et al. (2019)	17	PAX
	15	flights
Haoran Yang et al. (2018)	27	PAX
Hangjun Yang et al. (2020)	47	flights
Wan et al. (2016)	83	PAX on short-and medium-haul in China
	28	PAX on short-and medium-haul in Japan
Rounded off to two significant digits. *selection of cases only **central values		

4.5 FIELD 4: INDUCED HSR DEMAND

An increase in transport supply induces additional traffic that would not occur otherwise. This phenomenon is known as induced demand. It is critical for assessing the environmental performance of HSR (D'Alfonso et al., 2015:120; Yao & Morikawa, 2005:1). In this chapter, I gather values for induced HSR demand and point out the most relevant project and market characteristics to such values. Similar to the previous chapter, the relevant sources from the literature corpus are classified into three categories: theoretical models as well as ex-ante and ex-post demand evaluations. Sources that deal with data from multiple HSR projects are included in the third subchapter. At the end of this chapter, I provide an overview over plausible values for induced HSR demand.

4.5.1 Theoretical Models

D'Alfonso et al. (2015) construct an economic model for a duopoly case of competition between HSR and air transport. They prove that under any circumstances, the entry of HSR into the transportation market induces additional demand (ibid.:123).

Westin & Kageson (2012:3) assume that between 20 and 40 % of HSR demand is induced, with 25 % being their central value. The same premises as mentioned in chapter 4.4.1 apply.

Yao & Morikawa (2005) construct an economic and transportation model to project the amount of short term induced demand from a planned Tokyo-Osaka maglev project. They carry out SP and RP surveys to estimate the parameters of the model (ibid.:372). They estimate that as the new maglev route is opened, 16.5 % of the corridor's new total travel demand across all modes (measured in number of trips) will be induced by the expansion (ibid.:380). Since they do not provide figures for the estimated mode share of the new HSR line, I am unable to calculate the share of induced demand among the new line's traffic.

4.5.2 Ex-Ante Demand Evaluations

Bueno et al. (2017), Matute et al. (2015) and Miyoshi & Givoni (2013) each report official ex-ante project demand projections for the Basque Y, CAHSR and HS2 (see chapter 4.4.2). While for CAHSR only 2.1 % of demand on the new HSR line is projected to be induced (Matute et al., 2015:107), the estimates for the Basque Y and HS2 are 11.5 % (Bueno et al., 2017:6) and 22.5 % (Miyoshi & Givoni, 2013:122). Bueno et al. (2017) measure demand in passenger kilometers, while Matute et al. (2015) and Miyoshi & Givoni (2013) use number of trips.

D. Zhang et al. (2019) carry out an original ex-ante demand projection for a HSR project on the Dallas-San Antonio corridor. They conduct a SP survey among 1,000 participants (ibid.:192). Assuming an average travel speed of 200 km/h, a fare of 113,20 US$ and departure headways of 10.6 minutes for the HSR line, they calculate that 38 % of the total projected travel demand on the corridor would be induced demand (ibid.:195). Since they do not provide figures for the projected mode share of the new HSR line, I am unable to calculate the share of induced demand among the new line's traffic. One has to take the high value for induced demand (which would turn out even higher when expressed relative to HSR demand instead of total corridor demand) with caution, since the study was funded by Virgin Hyperloop One, a company that has an interest in demonstrating the commercial viability of such as project to secure public support and funding.

4.5.3 Ex-Post Demand Evaluations

Dalkic et al. (2017) perform a SP survey among 421 HSR users to estimate ridership distribution in a non-HSR scenario (ibid.:16f.). They find that on both the Ankara-Eskisehir and Ankara-Konya route, 3 % of respondents stated that they would not have travelled if the HSR did not exist (ibid.:18). This comparatively low value could be partially explained by respondents being more easily able to envision themselves using a different mode for their trip than imagining not travelling at all.

Givoni & Dobruszkes (2013) conduct a meta-study of ex-post HSR demand evaluations. They report a value range for induced traffic as a share of HSR ridership of 6 % (Osaka-Hakata) to 27 % (Paris-Lyon) (ibid.:728). The same authors further substantiate this wide range of values in a different source from the same year (Dobruszkes & Givoni, 2013:180f.). Givoni & Dobruszkes (2013) conclude that after two to four years of operation, about 20 % of HSR demand will be induced. Due to a large standard deviation, they recommend to assume values of 10 - 20 % for planning purposes where modelling it not possible (ibid.:737).

In their ex-post review of air and rail passenger development on the Madrid-Barcelona route, Lopez Pita et al. (2012:125) report that from 2007 - 2008, as HSR was introduced, air passenger numbers fell by 1.2 million while rail passenger numbers rose by 1.3 million to a total of 2.1 million. Using these figures, induced demand would only account for about 5 % of total rail demand. However, the number of rail passengers does not indicate the average travel distance. Hence, rail passengers shifting from CR to HSR undertaking longer journeys could be responsible for hidden induce demand in terms of passenger kilometers.

Baron et al. (2011) report ex-post induced demand data for the Valence-Marseille HSR line from RFF & SNCF (2007). According to the primary source, the TGV network added an additional 4,461,000 yearly journeys (ibid.:9) of an average distance of 600 km, while air and road transport together lost 2,970,000 journeys (ibid.:75). This translates to 1,491,000 induced trips, or 33.4 % of total new HSR traffic.

Cascetta & Coppola (2015) provide the only original, empirical ex-post evaluation of HSR induced demand in the literature corpus. Based on SP and RP surveys as well as train, highway and air transport data they calculate mode shares and mode shifts in the parts of Italy accessible by HSR. Of the 13.8 million additional yearly HSR trips added between 2009 and 2013, 5.5 million are induced (ibid.:14), translating to a share of induced demand of 40 % relative to the total HSR demand added. The same shortcomings of the used data as mentioned in chapter 4.4.4 apply.

4.5.4 Methodological Remarks

The sources analyzed in this chapter regard short- and medium-term induced demand. Long-term induced demand (also known as secondary induced demand) that results from slow changes in location choice and land use patterns is not sufficiently taken into account. Due to the long-term and gradual nature of such changes, capturing them ex-post using empirical methods is challenging.

Yao & Morikawa (2005:380) calculate price elasticities of travel demand of -1.5 to -1.7 for the Tokyo-Osaka corridor, demonstrating that fares and ticket prices are highly relevant to inter-city travel demand. Most sources however do not separately take into account price effects and other effects of HSR introduction (such as reduction in travel time). This contributes to the large range of induced demand values across HSR projects, as fares and changes in price levels due to HSR introduction vary.

4.5.5 Interim Conclusions

As with mode shift, the scale of induced demand varies strongly across different HSR projects. Besides methodological differences, this is because HSR projects result in different impacts on the general transportation market. HSR projects that decrease travel time or travel costs on a corridor below the level of the most competitive incumbent alternative mode will result in a higher share of induced demand (such as HS2 vs CR, or Paris-Lyon HSR vs CR or air transport) as there are a lot of journeys not viable previously that are now realized. On the other hand, HSR projects that roughly draw level with alternative modes (such as Madrid-Barcelona vs air transport) might still lead to sizable mode shifts, but do not cause as much induced demand, as the overall attractiveness of the journey along the corridor is not drastically improved.

The finding of Givoni & Dobruszkes (2013) that induced demand relative to total HSR demand usually is about 20 % and should be assumed to be between 10 and 20 % if no precise estimations are available matches the findings from the literature review. In extreme cases however, for the reasons laid out in the prior paragraph, induced demand as a share of HSR demand might plausibly take values between 2 and 40 %, as demonstrated in Table 19.

Further research should be conducted to gain insight into the magnitude of secondary (long-term) induced demand due to HSR projects, the magnitude of which is currently unclear. In addition, the sources present in the literature corpus largely report demand figures from other primary sources. I attribute the lack of original demand forecasts to the setup of the systematic literature review. Due to the same challenges as mentioned in chapter 4.4.5, separating price effects from other HSR impacts in empirical demand evaluations is difficult. For future demand projections such as

transportation models or SP surveys, including fares is as important as including travel time in order to attain realistic values for not only mode shift but also the amount of induced demand.

Table 19: Induced demand of HSR projects

Source	Induced demand [%] of total HSR demand	Notes
Matute et al. (2015)	2.1	CAHSR
Dalkic et al. (2017)	3	Ankara-Eskisehir and Ankara-Konya
Lopez Pita et al. (2012)	5	Madrid-Barcelona
Bueno et al. (2017)	12	Basque Y, passenger kilometers
Miyoshi & Givoni (2013)	23	HS2
Baron et al. (2011)	33	Valence-Marseille
Cascetta & Coppola (2015)	40	Italy
Westin & Kageson (2012)	20 - (25) - 40	Assumed range
Givoni & Dobruszkes (2013)	6 - (10 - 20) - 27	Meta-study
Demand measured in number of trips unless indicated otherwise. Rounded off to two significant digits.		

4.6 FIELD 5: COMPLEMENTARY EFFECTS

The impacts of HSR covered in chapters 4.4 and 4.5 are well known and studied. Complementary effects between HSR and alternative modes however, i.e. increases in air, road or other traffic due to the introduction of HSR, are less extensively researched (Albalate et al., 2015:1; Dobruszkes & Givoni, 2013:738). In this chapter, I provide an overview over complementary effects of HSR introduction on alternative modes, most prominently air transport. First, findings from the literature corpus about competition between HSR and airlines, mainly centered on prices, are analyzed. Then, I look into how HSR affects competition among airports. The third subchapter deals with the integration of HSR and air transport (such as by code sharing agreements or multimodal integration of HSR stations and airports). In the fourth subchapter, I look more closely at the impact of HSR introduction on airports operating under capacity constraints. Lastly, findings that relate to HSR's general spatial economic impact and how that might increase traffic in alternative modes are presented. At the end of this chapter, I point out methodological limitations, policy implications and further research needs.

4.6.1 Competition between HSR and Airlines

D'Alfonso et al. (2016) conduct a simulation study on the London-Paris travel market. The authors construct an economic model and derive parameters from literature and several official sources not further specified (ibid.:13). They find that increasing competition from HSR causes airlines to reduce airfares, which in turn induces new air traffic that would not take place at the previous price level (ibid.:16f.).

Gu & Wan (2020) construct an economic model and verify their theoretical findings using a regression analysis on the Chinese market (see chapter 4.4.4). They too find that the introduction of HSR reduces airfares, and that this can even be the case when air traffic increases overall (ibid.:58). Air traffic on routes where air transport is more than 5 hours faster than HSR increases, but the authors cannot attest whether decreasing airfares are the driving force behind this due to a lack of price data (ibid.:58,64).

Su et al. (2019) carry out a regression analysis on the Chinese air transportation market to investigate the impact of HSR on airlines' pricing strategy. They use data from 22 city pairs during the year 2016. The data contains flight and fare information for the 30 days before departure, resulting in over 2 million observations (ibid.:2). The authors find that HSR reduces airfares and pressures airlines into adopting LCC business models. Airlines should focus on long-haul routes to avoid competition with HSR (ibid.:9). These findings are repeated in a later publication by the same authors based on the same regression analysis (Su et al., 2020:43).

In their regression analysis on domestic flight routes in China, Japan and South Korea (see chapter 4.4.4), Wan et al. (2016) find that HSR increases the number of airline seats on long-haul routes in China by 28 %, as airlines divert capacity away from short- and medium-haul markets (ibid.:542). However, seats are reduced again on these routes as an even faster HSR service is introduced later (ibid.:551).

Xia & Zhang (2016) construct an economic model to investigate impacts of competition and cooperation of HSR and air transport on fares and traffic volumes in different transportation markets. Figure 12 depicts the assumed market structure. They find that increasing the speed of HSR (which also includes the introduction of a new HSR service) decreases airfares on competing routes.

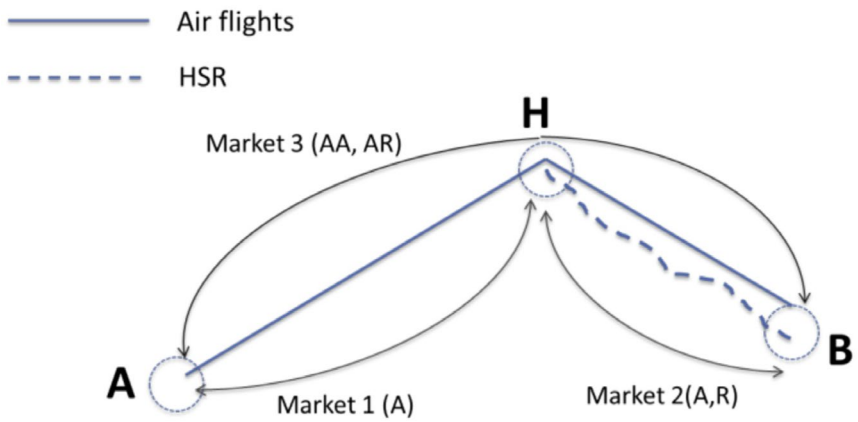

Figure 12: Generalized market structure (Xia & Zhang, 2016:462)

Hangjun Yang et al. (2020) construct an economic model of business class and economy class passengers' utility and estimate the model parameters using a regression analysis on 280 Chinese air routes (see chapter 4.4.4). They find that airfares on short-haul routes do not change significantly as HSR is introduced, but drop slightly for medium- and long-haul markets. They attribute this to the fixed fleet size, meaning that supply cannot be cut but is instead reallocated to less competitive markets (ibid:7). They estimate the elasticity of air transport demand measured in the number of business class and economy class passengers against changes in airfares at -0.21 and -0.75 respectively.

4.6.2 Competition between Airports

Terpstra & Lijesen (2015) put forward a regression analysis on five airports affected by the Amsterdam-Brussels HSR line and five airports affected by the Madrid-Barcelona HSR line. They investigate the role HSR plays for the competition among airports. Endogenous variables are flight frequency, airport access time, average fares and a dummy variable for each airport. Airport passenger numbers are treated as exogenous (ibid.:269). They use geo located booking data from 2007 and 2008, which allows them to select only bookings that took place in a 250 km radius around the two major airports for each HSR line. They calculate average fares for every route and booking agency as well as average logarithmic frequencies of direct flights between airport pairs (ibid.:266f.). Looking only at destinations where passengers have at least two origin airports to choose from, this data allows them to estimate parameters for a passengers' airport choice model (ibid.:269f.).

The authors find that passengers' airport choice depends on flight frequency, access time and average fare in that order. As the large hub airports offer higher frequencies and HSR expands their catchment areas, these hubs gain market shares at the cost of smaller, less competitive airports (ibid.:273). These smaller airports are increasingly forced to cater to passengers with a low

willingness to pay, for example by focusing on the LCC niche (ibid.:274). F. Zhang et al. (2018:208) confirm this, citing Cologne Bonn and Brussels National Airport as examples for such airports sandwiched between larger hubs that increasingly cater to LCC as a result of the introduction of HSR.

4.6.3 Integration of HSR and Air Transport

In chapter 4.4, I lay out how HSR can attract traffic away from air transport. While it is widely believed that integrating HSR and air transport, for example by code sharing or integration of a HSR station at an airport, increases this substitution effect and therefore reduces overall air traffic, there is a large body of theoretical and empirical evidence that speaks against it. Dobruszkes & Givoni (2013) compile such evidence in a book chapter dedicated to clarifying common myths about the relationship of HSR and air transport. According to the authors, HSR increases airports' catchment areas, leading to flying in general becoming more attractive. The environmental benefit from the substitution of feeder flights is marginal compared to such more general aviation impacts. This is because the emissions from connecting long-haul flights are by an order of magnitude larger than those from the substituted feeder flights (ibid.:191). This judgment is confirmed in a meta-study by A. Zhang et al. (2019:10), who conclude "[...] that air-HSR integration might impose a threat to the environment, as HSR tends to feed international flights that emit more relative to short-haul domestic flights due to longer flying distance".

Others sources also support this argument. Gu & Wan (2020:65) find this feeder effect to be especially pronounced when the HSR feeder journey is shorter than 2 hours and the air leg is long, reinforcing the argument by A. Zhang et al. (2019). In a regression study on airport-level traffic in China and Japan (see chapter 4.4), Liu et al. (2019:124) find that intermodal connectivity (i.e. a HSR station at the airport) positively correlates with the number of passengers enplaning. F. Zhang et al. (2018:208) confirm this in a regression study about European and Asian airports, stating that integration of air transport and HSR at an airport correlates with an additional 3 to 8 million passengers a year, and even more if the airport is a hub. In an economic model similar to Xia & Zhang (2016), Jiang & Zhang (2014:46) demonstrate that the introduction of HSR parallel to one flight route increases air traffic on connecting, longer routes without HSR competition.

4.6.4 Short-Haul Substitution under Capacity Constraints

Airports that are being connected to the HSR network or where other forms of air-HSR integration take place tend to be hub airports and operate under capacity constraints (Givoni & Dobruszkes, 2013:738). The substitution of short-haul flights by HSR at capacity-constrained airports might

create additional air traffic, since the slots formerly used for short-haul flights are now allocated to additional medium- and long-haul flights. This increases air passenger kilometers and GHG emissions from air transport, even if the number of flight movements at an airport stays constant. Additionally, long-haul air routes tend to be served by larger aircraft, further increasing air transport volume and GHG (Dobruszkes & Givoni, 2013:191; A. Zhang et al., 2019:10; F. Zhang et al., 2018:208).

Jiang & Zhang (2014:173), Socorro & Viecens (2013:475) and Xia & Zhang (2016:46) confirm this observation using economic models. Freed up slots are used for more welfare-enhancing flights and flights on routes where competition by HSR is low. HSR therefore enables a substitution of short-haul by medium- and long-haul flights. Dobruszkes et al. (2014:473) and F. Zhang et al. (2018:208) perform regression analyses on European and Asian markets (see chapter 4.4.4) and also confirm this relationship. Similar to the previous subchapter, they point out that the emissions from long-haul flights can be by an order of magnitude larger than those of the substituted short-haul feeder flights.

4.6.5 Economic Stimulation

Two sources point out examples of how HSR can stimulate the affected region's economy in such a way that in certain travel markets transportation volumes of modes other than HSR rise. In their regression analysis on the Asian market, F. Zhang et al. (2018:200) finds that HSR increases air traffic on routes longer than 1,000 km. That is because

> "[…] [HSR links] might have initiated a number of social and economic activities which generated induced demand for travel. Part of the induced travel demand later spread onto other competitive transport modes such as the aviation service. As the result, the intervention of HSR reinforced instead of reducing[sic] the travel demand by air" (ibid.:203).

Borsati & Albalate (2020) put forward one of the few original, empirical studies in the literature corpus that focus on the modal shift between private cars and HSR. They assess the impact of HSR introduction and intra-HSR competition on the Italian market. The authors perform a panel regression on traffic volume data on tolled motorways sections parallel to new HSR lines. Their findings are contrary to those of Cascetta & Coppola (2015) (see chapter 4.4.4). Borsati & Albalate (2020) find that HSR does not lead to a reduction in highway traffic. Instead, a 10 % increase in HSR length leads to a 0.55 % increase in vehicle kilometers travelled on parallel motorway routes. This finding is significant at the 5 %-level (ibid.:13f.). The authors point out several explanations for this counterintuitive relationship. Private cars and HSR might be non-competing, because door-to-door travel time is still shorter by car than by HSR in most cases. Also, the introduction of HSR may induce economic growth in the affected regions, leading to an increase in car traffic (ibid.:19). These

findings supplement the results of F. Zhang et al. (2018), indicating that especially in travel markets that are not main competitors of HSR, the economic stimulation caused by such projects might increase total traffic.

4.6.6 Methodological Remarks

As with all regression studies, the correlations found must be interpreted carefully. For example, the regression studies that find that air traffic increases at airport-level as HSR is introduced cannot assert whether this results from a shift of traffic from other, less accessible airports, or whether the integration of HSR and air transport induces new air transport demand. It is also likely that airports that experience disproportionate growth are more likely to be equipped with a HSR station by planners and policy makers.

While many sources point out that improving the accessibility of airports and especially hubs might result in travelers choosing more distant destinations, no study in the literature corpus investigates the determinants of travelers' destination choice.

The literature corpus contains no source that quantifies the impact of HSR on airfares. Price elasticities for business and economy class air transport demand of -0.21 and -0.75 (Hangjun Yang et al., 2020:5) demonstrate that such changes in airfares, even if small, can have a sizeable impact on overall air transport demand. The impact of competition from HSR on airfares are reflected on a route level where there are due to the first occurrence of competition on that route, since airlines have to relinquish their premiums. Where they are due to a now oversized fleet they are likely negligible on a route-level but relevant on a system-wide level, since airlines will shift capacity to other routes.

4.6.7 Interim Conclusions

Competition from HSR forces airlines to reduce airfares and adopt LCC business models, inducing additional air transport demand. Especially in markets with a low degree of competition and high premiums by incumbent airlines, such as China (D. Zhang et al., 2019:5), intermodal competition can play the role that intramodal competition plays elsewhere. One can conclude that the impact of HSR on airfares and LCC prevalence is weaker in regions with strong competition between airlines (such as Europe) than in regions with less competition (such as China). In the short- and medium-term, fixed fleet sizes making it difficult for airlines to adjust supply strengthen this impact.

The reviewed sources also provide evidence that HSR pressures airlines to divert their resources from short- to medium- and long-haul flights, where there is less competition from HSR. On one hand, airplanes used for long-haul flights spend a higher share of their time in-air, resulting in higher emissions. On the other hand, fewer take-offs and landings as well as higher occupancy rates for long-distance flights might counteract this increase in emissions. The sources indicate that shifting airlines' resources to longer flights is generally detrimental to the environment. However, these effects do not hold up long-term, since airlines can adjust their fleet size to the new competitive situation over time. The shift toward longer flights can be permanently reinforced by the substitution of short-term feeder flights for HSR, since at capacity-constrained airports the freed up slots are now available for longer flights.

Hub airports profit disproportionately from improvements in accessibility, as they are more attractive to travelers than smaller airports. As HSR increases hub airports' catchment areas, smaller airports are frequently pressured to cater to LCC. The literature also agrees that increasing the accessibility of airports, especially hubs, increases the attractiveness of flying, especially for long-haul flights. However, I find no concrete values for induced (long-haul) air transport demand as a reaction to improved (hub) airport accessibility.

There is sporadic evidence that in niche markets that do not compete with HSR, HSR increases traffic volumes due to economic stimulation. Since these niche markets are usually not thought of as main competitors to HSR (such as long-haul flights or road transport), they might be overlooked when assessing HSR's environmental impact. In transportation project appraisal, wider economic benefits of a project are often included. These could be abated by a fixed ratio related to carbon intensity of the stimulated growth to account for such increases in GHG emissions. However, since this impact is small compared to other effects found in this chapter, strongly depends on the economic status of the affected region and economic components of project appraisal processes are not a focus of this research paper, I exclude it from further considerations.

I conclude that HSR does not lead to a reduction of GHG emissions from air transport on a system-level, due to complementary effects and air transport adapting to the new competition. This finding is resonated by Dobruszkes & Givoni (2013:193f.) and A. Zhang et al. (2019:11). To have HSR alleviate GHG from air transport, additional policy measures would have to be taken. To avoid freed-up capacities of air transport to be used for longer flights or to lower prices, supply would have to be reduced after HSR is introduced. For example, regional airports whose catchment areas overlap with those of larger hub airports after HSR is introduced could be downsized or even shut down. Price reductions due to HSR competition could be counteracted by adjusting taxation on air transport to levels found in other modes. More generally speaking, policies on HSR and air transport should be realized in push-and-pull packages. As introducing HSR increases transport supply, air transport should be disincentified to support mode shift from HSR to air transport while avoiding rebound effects. Reducing air transport supply (i.e. increasing costs) might be

unpopular politically, but is easier to justify in combination with measures such as new HSR infrastructure.

Regarding further research needs, one can attest that complementary effects between HSR and air transport are insufficiently studied. To quantify the impact that improving the accessibility of (hub) airports has on the attractiveness of (long-haul) flights, I propose augmenting the research by Terpstra & Lijesen (2015) about passengers' airport choice with a model for passengers' destination choice. A. Zhang et al. (2019:10) propose a nation-wide flight emission study to estimate overall changes in GHG emissions from air transport due to a growing HSR network. I propose that such a nation-wide flight emission study should also include the impact of airfares and the dependence of travelers' destination choice on hub airport accessibility. In a nation-wide study, it would be challenging to single out HSR impacts versus national trends such as overall changes in demand or price, which would apply to all data points. An international study comparing developments in multiple markets could alleviate this issue, but would face other challenges such as data availability and comparability. Lastly, while price elasticities of air transport demand are extensively studied (albeit only sporadically included in the literature corpus), the impact of HSR on airfares should also be more closely examined, as only the combination of both allows to quantify the scale of complementary induced demand in air transport due to price competition from HSR.

5 DISCUSSION

In this chapter, the results from the systematic literature review across all five research fields are discussed. I focus on issues that span more than one research field or that pertain to the overall impact of HSR. First, I discuss important findings regarding the methodology of studies and the varying delimitations of several terms that are central to the overall impact of HSR. Then, the overall impact of HSR on spatial equity and the environment is deliberated. In the fourth subchapter, I lay out the policy implications of these findings. Lastly, further research needs regarding the overall impact of HSR and possible study designs are brought forward. The individual, more detailed findings for every research field are found at the end of the respective chapters 4.2 to 4.6.

5.1 METHODOLOGY AND DELIMITATIONS

Interpretation of the results from chapter 4.2 regarding the impact of HSR on spatial equity demands a closer look at the difference between spatial equity on one hand and equalization of accessibility measures on the other. I define equity of living conditions in chapter 2.3, where I point out that it describes the political goal to ensure a basic level of accessibility to periodic and specific goods and services even in peripheral areas. This alone does not require equalizing accessibility of peripheral and metropolitan areas. Projects that improve accessibility in peripheral areas but do so even more in already well-connected regions therefore might still contribute to spatial equity. However, the findings from the literature do not provide conclusive insights into how this interacts with improving the economic competitiveness of peripheral compared to metropolitan regions. In addition, the sources from the literature corpus do not provide insight into whether there might occur a rebound effect, where improving transport infrastructure in peripheral regions could lead to a further centralization of periodic and specific goods and services.

As demonstrated in chapter 4.3.4, the GWP of a ton of CO2 emitted by air transport is higher than that of road or rail transport due to a RFI of about 1.7. Most sources neglect to take this into account. This results in a systematic underestimation of the positive environmental impact of mode shift, but also in an underestimation of the negative environmental impact of complementary effects.

In the literature, a shift of demand is usually attested when demand declines in one mode and rises in another. Likewise, induced demand is assumed to be the difference between journeys (or other measures of demand) shifted from competing modes to for example HSR and the total increase of journeys undertaken via HSR. However, these seemingly straightforward relationships are more ambivalent, especially if one includes complementary effects from chapter 4.6 (i.e. that demand can be induced in several modes at once).

Assume the following example: an existing HSR service transports 10 million passengers per year, and parallel flight services carry 5 million passengers per year. Improving the HSR infrastructure reduces its travel time and afterwards, 13 million journeys are undertaken via HSR and 3 million via air transport. One could conclude that 2 million air transport journeys were shifted to HSR and 1 million HSR journeys are induced. However, it could also be that HSR in fact attracted 3 million instead of just 2 million trips from air transport, and that an additional 1 million passengers now travel using air transport who would not have travelled previously, for example due to falling airfares or improved accessibility of airports. Alternatively, a decline in flight frequency could have caused 1 million air passengers to cease travelling altogether, meaning only 1 million air passengers switched over to HSR and that 2 million HSR journeys are induced traffic.

The example demonstrates that one is unable to attest how individual (potential) passengers change their travel patterns by just looking at traffic volumes before and after a project. To gain insights into individuals' travel choices, surveys or economic models and simulations are necessary. One should scrutinize estimates for mode shift and induced demand, especially from sources that report ex-post values for those and that do not regard the relationship between the two and complementary effects. While the environmental impact of the introduction of HSR in the example case is the same regardless of how travelers move between modes and not travelling, the impact could be attributed to different mechanics. In addition, estimates for the general potential of HSR to result in mode shift or induced demand are distorted.

Price levels and competition are highly relevant for mode shift, induced demand and complementary effects. In most empirical studies however, ticket prices are not included as price data is difficult to obtain. HSR and airfares also exhibit a high intertemporal volatility. Even fewer sources look at generalized costs or other combined measures. Even if accurate price data were available, linking them to changes in HSR infrastructure would be challenging compared to more infrastructure related measures such as travel time.

Regarding studies that assess the overall environmental impact of HSR (predominantly found in chapter 4.3 and 4.4) I find two general approaches. One is calculating the carbon intensity of HSR per passenger kilometer, comparing them to carbon intensities of alternative modes, and, assuming a certain value for mode shift and a life span, calculating the total environmental benefit in terms of GHG emissions avoided over the project's lifetime. One can interpret these avoided emissions as a social welfare gain, hence qualifying this approach for benefit-cost-analyses. The other approach is to estimate emissions from construction and operation separately, and calculating the time needed for a certain mode shift to offset initial emissions from infrastructure construction. This approach is especially useful if one wants to assess whether HSR has a net positive environmental impact at all. It also allows the evaluators to apply carbon discounting rates that assign earlier GHG emissions a higher weight than GHG emitted later on and to evaluate whether a HSR project is able to contribute to climate change mitigation early enough to reach global warming targets. In addition, assumed lifespans for infrastructure vary between 40 and 100

years. It is not feasible to project other factors such as carbon intensity of the electricity mix or of alternative modes over such long time spans. Assuming that a HSR project breaks even in terms of GWP earlier than its end of life, the second approach can deliver recuperation periods without requiring data about such factors for times after its break-even point.

5.2 OVERALL IMPACT OF HSR ON SPATIAL EQUITY

The sources from the literature corpus agree that HSR network expansion generally increases accessibility across all parts of the examined area, but even more so in already well-connected metropolitan areas. Especially the first finding must be scrutinized due to the methodological limitations pointed out in chapter 4.2.2. Increasing accessibility of peripheral regions improves spatial equity, as inhabitants can now access periodic and specific goods and services more easily. This certainly holds true in the short term but rebound effects (meaning that such goods and service concentrate in fewer locations as transport infrastructure and catchment areas are expanded) could in part mitigate this impact in the long term. Onward connectivity from HSR stations to areas not directly accessed by HSR, especially by CR, is also highly relevant.

The economic impact of HSR connections on small en-route cities is more ambivalent than discussed in public discourse. The most important determinants for success (i.e. that the spillover-effect outweighs the siphon-effect) are that the city is within two hours of a larger city which experiences negative agglomeration effects and that the smaller city already has a well-developed service sector. If these criteria are not met, a HSR connection can even have an adverse impact on the smaller city's economy. In the long term, HSR service cannot be taken for granted at small en-route stops, especially as the network is expanded and if the city fails to attract growth in industries that generate additional HSR demand.

5.3 OVERALL IMPACT OF HSR ON THE ENVIRONMENT

HSR projects can have vastly different carbon intensities, ranging from 10 to 283 gCO2/pkm. The most important determinants are the number of passengers, the share of bridge and tunnel sections and the carbon intensity of the electricity mix used for train propulsion. While many studies and project appraisals only regard operation, construction is just as relevant to the environmental impact of a HSR project, accounting for the majority of emissions in some cases. The GWP of HSR can be worse than that of air transport in cases where the line involves a high share of earthwork or aerial structures and passenger numbers are low, even when accounting for an RFI of 1.7 for air transport. In such cases, HSR will always be detrimental to the environment. It is therefore not self-evident that HSR is beneficial to the environment.

Even if HSR has lower carbon intensity than competing modes, its overall environmental impact can still be negative due to induced demand and complementary effects possibly outweighing the positive impact of mode shift. Concrete values for mode shift and induced demand are very variable, depending on route characteristics and the incumbent transportation market. While mode shift can take almost any mathematically feasible value (see Table 17 and Table 18), induced demand frequently varies between 10 and 20 % of total HSR demand, with outliers ranging between 2 and 40 %. I find five complementary relationships by which HSR causes substantial additional environmental burdens from air transport:

1. Price competition between HSR and airlines. HSR reduces airfares in two ways: where it poses as the first competitor to an incumbent airline, it forces the airline to reduce price premiums that it was able to collect previously due to being a monopolist. In addition, mode shift of journeys from air to HSR reduces demand, but airlines are not able to reduce their supply in the short-term. This results in airlines further reducing their prices, which in turn induces additional air transport demand that partially offsets the original mode shift to HSR.
2. Airlines' evasion of competition. Because of price competition, airlines shift parts of their supply to routes where they experience less competition from HSR, such as medium- and long-haul. Even with identical supply in terms of fleet size, this results in higher emissions compared to previous flight portfolios.
3. Competition between airports. As HSR expands the catchment areas of airports, and hub airports generally being more attractive to passengers than small regional airports, air traffic concentrates at hubs. This creates economic pressure on the remaining regional airports to stay in business by reducing prices for customers and airlines, sometimes culminating in the development of dedicated LCC airports.
4. Substitution of short-haul by long-haul flights. As HSR substitutes short-haul flights at capacity-constrained airports, the freed-up capacity does not lay barren. At hub airports, runway capacity often is the major bottleneck, and the substitution of former feeder flights by HSR allows those slots to be used by medium- and long-haul flights, resulting in a drastic increase in GWP from air transport.
5. HSR as a feeder to air transport. As HSR improves the accessibility of airports (especially hub airports), flying in general becomes more attractive. By lowering travel time and improving comfort across the travel chain, HSR induces additional air transport journeys to which it feeds passengers. This especially applies to long-haul flights that are usually only available at hub airports and do not compete with HSR.

Since concise values are not available, it is difficult to weight these complementary effects against the more easily quantifiable environmental benefits of HSR. Overall, I agree with the judgements found in the literature corpus that HSR does not reduce total GWP from air transport. While HSR competition might reduce emissions on a route level, reactions of the air transport economy will

result in equal or higher emissions on a transportation system level. This holds true even more so in the short term, where supply such as airport capacity and fleet size does not adjust easily, and assuming no restricting policy measures are being taken.

This paper demonstrates that the environmental impacts of HSR projects need to be examined on a case-to-case basis, with special attention being dedicated to mode shift forecasts and embedded emissions. Unlike suggested by public discourse, new HSR lines are not guaranteed to create a positive impact on the environment, especially when it comes to secondary lines and lines involving challenging terrain. I was not able to quantify complementary effects based on the results from the systematic literature review. Further research is needed to include such effects in project appraisal.

5.4 POLICY IMPLICATIONS

HSR can be a viable policy tool to improve equity of living conditions. However, considering the low economic and ecological practicality of secondary lines, it should be called into question whether simply providing periodic and specific goods and services more locally could be a more efficient and sustainable use of resources compared to the construction of new transport links.

The need to assess the environmental impact of specific HSR projects on a case-to-case basis must be reflected in a vigorous project appraisal process. The accuracy of demand forecasts has already been discussed and will continue to be a topic of research. However, more attention should be dedicated to the influence of construction parameters on the carbon intensity of HSR infrastructure. For example, the German Federal Transport Infrastructure Plan differentiates the carbon emissions from the construction of new railways by two types of lines, namely lowlands and low mountain ranges (PTV Group et al., 2016:438). In the light of the findings of this paper, a more detailed appraisal of embedded emission seems appropriate.

For HSR as a transportation system to contribute to a reduction in GHG emissions and a mitigation of climate change overall, the findings of this paper have a number of policy implications. A sole expansion of HSR infrastructure and service is unlikely to achieve such policy goals, as air and road transport infrastructure remain in place and there are several complementary relationships. Instead, policy measures that expand (pull) and restrict (push) transportation supply should be combined in push-and-pull packages. This way, a mode shift to less carbon intense transportation modes can be realized while compensating for induced demand and complementary effects. Such restrictive measures could include raising fees and taxes on environmentally disadvantageous modes, align workers' rights in air with rail transport, and reducing capacity by expanding bans on night flights or closing small regional airports.

On their own, such supply-restricting policies can be politically challenging. By combining them with expansionist measures such as new HSR infrastructure policy makers not only create policy packages that are more likely to achieve GHG emission targets. By ensuring an overall constant level of transportation supply and mobility to the populace, such push-and-pull packages also allow to build a compelling narrative justifying the otherwise unpopular measures.

5.5 FURTHER RESEARCH NEEDS

For the final part of this paper, I present research needs and study proposals regarding the overall environmental and accessibility impacts of HSR. As with the previous subchapters, research needs pertaining to just one specific research field are dealt with in the respective subchapters in chapter 4.

To further evaluate the suitability of HSR projects as a tool to increase spatial equity in the long term, research should be carried out that investigates how the spatial distribution of periodic and specific goods and service changes after the introduction of HSR. It is possible that expanding transport infrastructure leads to a further concentration of such amenities, partially offsetting the increase in accessibility of such goods from peripheral areas. To substantiate the claim that the expansion of HSR networks increases total accessibility for every place, even in fringe cases, studies such as by Cascetta et al. (2020), Cavallaro et al. (2020) and Zhu et al. (2015) should be repeated using a finer spatial resolution. Special attention should be dedicated to declines in CR services and transfers. I find sporadic evidence that by including these factors, accessibility for some places can indeed decrease as HSR is introduced.

This paper provides some reference values for the carbon intensity of HSR infrastructure. To include such values in project appraisal, more country-specific research is needed. This includes national values for carbon intensities as well as an effective set of route types.

Complementary effects are almost exclusively researched in regards to HSR and air transport, with only one source in the literature corpus investigating complementary effects between HSR and other modes, namely road transport. Future research should put more emphasis on mutually reinforcing relationships between HSR and modes other than air transport. Future regression studies that investigate the relationship between HSR introduction and HSR or air transport demand should, whenever possible, refrain from capturing HSR by using a dummy variable. The scale of mode shift, induced demand and complementary effects depends on the differences in service quality such as travel time, costs or number of transfers. Classifying routes simply by whether there is a competing HSR service does not capture these differences and therefore does not allow for comparisons of the identified elasticities with other studies. Instead, continuous variables such as (difference in) travel time, costs or even generalized costs should be used. I point out the relevance and methodological issues regarding price data in chapter 5.1.

Multiple sources point out that by improving the accessibility of hub airports, HSR renders long-distance flights more viable to customers and leads to an increase in long-distance air transport demand. It is challenging to capture this effect by comparing traffic volumes between airports, since improving an airport's HSR connection also causes existing passengers to shift between airports. Instead, the passengers' airport choice model by Terpstra & Lijesen (2015) should be complemented by a model for passengers' destination choice. More concretely, using similar data and methods as the original authors, the influence of the accessibility of an airport offering long-distance flights from passengers' places of residence on passengers' decision whether and where to travel should be examined. This would allow quantifying induced long-distance air travel demand due to improved HSR accessibility of hub airports. SP surveys regarding passengers' destination choice are less suitable for the reasons laid out regarding Dalkic et al.'s (2017) work in chapter 4.5.3.

To estimate overall changes in GHG emissions from air transport due to an expansion of the HSR network, A. Zhang et al. (2019) propose a nation-wide flight emission study. I too recommend such an approach. Most of the existing literature examines changes in air traffic due to HSR introduction on a route or airport level. By looking at changes in flight emissions against changes in HSR supply on a national level, one could investigate the combined effect of substitution and complementation. For example, airlines adapting to competition from HSR by shifting resources to routes with less competition is not captured by current study designs. In addition, average levels of HSR and airfares could be included more easily than route-specific price data. However, compared to studies at route or airport level, singling out the impact of HSR expansion versus other national trends such as overall changes in economic growth would be challenging, since there is no control group to compare the treatment group against. An international study comparing developments in multiple markets could alleviate this issue but would face other challenges such as data availability and comparability.

As pointed out throughout this paper, the net environmental impact of HSR varies strongly depending on the parameters of an individual project. Therefore, it is not useful to state the average environmental impact of HSR as a transportation system. However, Westin & Kageson (2012) demonstrate a useful approach how the data compiled in this paper can nevertheless be used for an overall judgement about HSR. The authors set up a Monte Carlo simulation, in which project parameters such as resulting mode shift, carbon intensity of electricity mix, share of tunnel sections and others are randomly varied. For different scenarios, they calculate probability distributions of the number of passengers needed in order for the project to cause a net environmental benefit. The ranges for carbon intensity, mode shift and induced demand demonstrated in this paper can be used to adjust those parameters' upper and lower bounds. I also propose treating passenger numbers as another randomized input and instead calculating the distribution of recuperation periods for different scenarios. That way, the ability of different types of HSR projects to contribute to the mitigation of climate change can be quantified.

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