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Impacts of High-speed Rail Projects on CO_2 Emissions due to Modal Interactions: A Review

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Abstract: This paper reviews existing literature on the CO2 emissions implications of high-speed rail (HSR) projects due to its interactions with air, road, and ordinary-speed rail. We conceptually classify the studies into three levels, with the first focusing on the emission comparison between HSR and the other modes, the second on the emission implication due to HSR-induced traffic reallocation, and the third on the life cycle assessment (LCA). We find that the literature is still in a relatively premature state. We also identify future research opportunities, including: i) to carry out a more detailed and comprehensive analysis regarding how HSR affects cargo operations of other transport modes and the corresponding CO_2 emission implications, ii) to further develop the game-theoretical models to be applied to estimate a fuller picture of modal splits and the corresponding CO_2 emission impacts, and iii) to apply LCA by considering the avoided life-cycle emissions associated with infrastructure and vehicles due to traffic diversion and the intricacies of modal interactions.

Keywords: High-speed rail; modal shift; emission; air transport; road transport; conventional rail

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1. Introduction

High-speed rail (HSR) has become a major mode of domestic transportation in many countries, and its network is still rapidly growing. Table 1 summarizes the lengths of HSR lines in operation and under construction in different countries in 2018.[1] It is anticipated that by 2025, the length of the world's HSR will more than double from the 2014 level (Givoni and Dobruszkes, 2013; Xia and Zhang, 2016; UIC, 2018). The HSR network has been a critical element in these countries to facilitate policies regarding economy, connectivity, and regional development. More recently, a major policy objective of HSR network development is to reduce the negative environmental implications of transportation. Challenges to global warming and the important role of transportation in meeting such challenges can be seen from Figure 1 below.

Insert Table 1 about here

Insert Figure 1 about here

The CO_2 emissions and environmental impacts of HSR have also attracted increasing attention during recent years in the literature. A research focus is the modal shift from other transportation modes to HSR. HSR is generally considered as a less environmentally detrimental substitute to air and road transportation (e.g., Givoni and Dobruszkes, 2013; Zhang et al., 2004). However, introducing HSR may also induce new travel demand. Givoni and Dobruszkes (2013) suggest that the induced demand accounts for about 20% of all demand of the HSR services after a few years

[1] From the table we can clearly see that most existing and planned HSR lines are in either Europe (especially West Europe) or Asia (especially East Asia). This is why most of the studies reviewed in this paper focus on these two geographical regions.

of operation.[2] In fact, even if the introduction of HSR leads to strong modal substitution, air traffic may not necessarily see a substantial reduction because induced demand, in this case to air traffic, can quickly fill up freed airport capacity. Therefore, it may be premature to conclude that HSR projects will definitely bring positive environmental impacts without a comprehensive evaluation covering all relevant transportation modes.

This paper aims to offer an interpretative review of the literature on the CO_2 emission implications of HSR's interactions with other transportation modes, including air, road, and conventional (ordinary-speed) rail. This literature review will focus on the empirical evidence and policy discussions. Such an environmental assessment is very important to policy making in countries with ongoing HSR developments, given that these projects involve huge amounts of public funds (Zhang et al., 2019). This literature review is also necessary as a large number of relevant scientific papers have been published over the past years, in various fields including transportation, economics, geography, and engineering. However, a closer look at the current research landscape reveals that these studies are still rather diverse and disparate, with a clear, integrated analytical structure not yet available. This deficiency would most likely present major challenges in deepening our understanding towards the relationship between HSR's interactions with other transportation modes and CO_2 emission in the transport sector, hindering the further development of this literature. Therefore, the main objective and contribution of this paper is not to introduce individual studies on this topic, but to present them in a logically integrated way. In particular, we construct a conceptual framework consisting of three levels of analysis differentiated by the focus of the studies. It is worth pointing out that the framework is a new construction of this paper and

[2] This is consistent with a recent study by Chen et al. (2021), which finds, in the case of Beijing-Shanghai HSR line that started its service on June 30, 2011, that from 2011 to 2017 the induced traffic accounts for 17.34% of the Beijing-Shanghai HSR passengers volume.

is not shared by the studies reviewed. The purpose of such construction is to provide a structure to incorporate all the existing research on this topic, as well as a solid foundation to help identify the limitations of the existing collection of work along the way. Through such an effort, we aim at offering a macro-view for future research to refer to and develop upon.

In order to obtain insights with sufficient focus, we need to define the scope of this literature review. First, we are only concerned about CO_2 emissions generated by the transportation services. The indirect impacts of transportation infrastructure on CO_2 emissions are out of the scope of this review.[3] Second, we focus on the comparisons or interactions between HSR and the other transport modes. Therefore, studies investigating the CO_2 emission implication of HSR projects without taking into account the other transport modes will also not be specifically discussed. These are usually life-cycle assessment (LCA) with an exclusive focus on new/proposed HSR projects, such as Chang and Kendall (2011), Jones et al. (2017), Chang et al. (2019), and Cheng et al. (2020).

The paper is organized as follows. Section 2 presents a conceptual framework that helps unify the relevant research into a three-level structure. Sections 3-5 discuss, one by one, the three levels of research regarding the environmental implications of the HSR-induced modal shift from other transport modes, respectively. Section 6 contains conclusions about the existing literature and discussions regarding possible avenues for future studies.

2. Conceptual Framework

[3] There exists some studies regarding the indirect impacts of HSR projects on CO_2 emission that go beyond the transportation system. For example, HSR projects can affect the relocation of industries and thus affect the discharge of CO_2 and other pollutants from such industries accordingly (e.g., Guo et al., 2021).

In this section, we will present a unified conceptual framework that incorporates all the existing studies regarding the impacts of HSR projects on CO_2 emissions due to modal interactions. The review suggests that relevant papers can be categorized into three levels, depending on the focus and the comprehensiveness of these studies. The first level investigates the emission rates (i.e., emission per unit of traffic) of HSR and the other transport modes. In general, this line of research pays less attention to the traffic implications of a new/proposed HSR project on other transport modes. In order to obtain the overall change of CO_2 emissions after the introduction of a new/proposed HSR project from these studies, an implicit assumption that all the HSR traffic is diverted from other transport modes needs to be made. With this assumption, the net CO_2 emissions impact (hereafter denoted as NE) due to the interactions between a new/proposed HSR project and other transport modes derived from the first level of research (represented by the subscript 1) in period t is given by:

$$NE_{1t} = \sum_i (e_h - e_i) Q_{it}^D \quad (1)$$

where e_h is the CO_2 emission rate of HSR, e_i is the CO_2 emission rate of transportation mode i, and Q_{it}^D is the diverted traffic from mode i to HSR in period t.[4] Other than HSR, the major transport modes that constitute the passenger transportation system are air transport, road transport (car and coach), and ordinary-speed railway (OSR). Here, we use $i = a$ to denote air transport, $i = co$ to denote coach, $i = ca$ to denote car, and $i = o$ to denote OSR. It should be noted that i does not include HSR. Among these three modes, OSR is likely the most controversial and contentious,

[4] One issue that is usually overlooked in the literature is that the CO_2 emission rate comparison is usually based on the unit per passenger kilometer (see details in Section 3). However, when a passenger switch from one transport mode to another, the travel distances of these two modes may not be the same. Therefore, Equation (3) is not entirely accurate to measure the CO_2 emission of modal substitution.

because it can also be argued that HSR and OSR are both sub-divisions within the railway sector. In this paper and some related existing studies, HSR and OSR are treated as two modes, because although there exist cases where certain infrastructure (e.g., some stations) is shared between the two, there is usually a very clear distinction between the two markets. For example, the National Development and Reform Commission of China has clearly differentiated HSR from OSR, citing the necessity of a more balanced development between the two (Global Times, 2021). Studies on the Chinese railway system also usually separate the two (e.g., Li et al., 2019; Sun et al., 2020; Cheng and Chen, 2021). In some markets such as Japan and Taiwan, HSR and OSR are 100% physically segregated from each other. Having said these, we admit that the boundary between HSR and OSR is not as simple and clear-cut as between HSR and the other transport modes (air and road). In the following sections we would see that this boundary also differs in importance in the three levels of analysis.

Admittedly, the assumption that HSR only attracts existing traffic from other transport modes and doesn't generate any additional traffic is rather strong. This is why the second level of research exists. The level studies the CO_2 emissions implication considering traffic reallocation due to the entry of HSR. In general, the entry of HSR may have three different effects on the traffic allocation among modes. The first is the traffic diversion effect identified in Equation (1). Many existing studies have investigated the substitution of other transport modes by HSR service. For example, relevant theoretical works include Adler et al. (2010), Yang and Zhang (2012), and Jiang and Zhang (2016), while empirical works include Behrens and Pels (2012) and Wan et al. (2016). The second is the newly generated HSR traffic. Such induced traffic is due to the fact that the introduction of a new transport mode or an improvement in the transportation systems can encourage people to take more trips (e.g., Givoni and Dobruszkes, 2013; D'Alfonso et al., 2015;

2016; Chen et al., 2019). The third effect is the newly generated traffic of other transport modes induced by the complementary relationship between this mode and HSR. For example, HSR can feed short-haul traffic to hub airports which can spur the demand for long-haul air flights. Some recent studies, both theoretical (e.g., Jiang and Zhang, 2014; Li and Sheng, 2016; Xia and Zhang, 2016; 2017; Xia et al., 2019; Zhang et al., 2019) and empirical (e.g., Liu et al., 2019), have shown that an introduction of HSR may actually increase air traffic at a hub airport. In summary, the conceptual description of the net CO_2 emissions impact of the interactions between HSR and other transport modes derived from the second level of research (represented by the subscript 2) in period t is:

$$NE_{2t} = \sum_{i}(e_h - e_i)Q_{it}^{D} + e_h Q_{ht}^{G} + \sum_{i} e_i Q_{it}^{G} = NE_{1t} + e_h Q_{ht}^{G} + \sum_{i} e_i Q_{it}^{G} \tag{2}$$

where Q_{ht}^{G} is the newly generated HSR traffic, while Q_{it}^{G} is the generated traffic of mode *i* induced by HSR, both in period t. Equation (2) can also be rearranged as:

$$NE_{2t} = e_h Q_{ht} - \sum_{i} e_i Q_{it}^{N} \tag{3}$$

where $Q_{ht} = Q_{ht}^{G} + \sum_i Q_{it}^{D}$ is representing the total HSR traffic in period t, while $Q_{it}^{N} = Q_{it}^{D} - Q_{it}^{G}$ is representing the net traffic change of mode *i* after the introduction of HSR in this period.

The third level focuses on the LCA which assesses the environmental impacts throughout a project's lifecycle (e.g., Guinée et al., 1993a; 1993b). In the case of transportation, LCA includes the inputs (i.e., energy) and outputs (e.g., emissions) from vehicles, infrastructure, and fuel production, each of which consists of construction, production, operation, maintenance, and end-of-life treatments (e.g., Chester and Horvath, 2010).

$$NE_{3t} = NE_{ct} + NE_{ot} = NE_{ct} + NE_{2t} \quad (4)$$

In equation (4), we use NE_{ct} to represent the net emissions from all the non-operation activities of the transportation system that occurred in period t, including infrastructure construction, maintenance and overhaul, aircraft/vehicle/rolling stock production, maintenance and overhaul, as well as the production of energy that powers the transport modes. It can be defined as the difference of CO_2 emissions from the non-operation activities with and without HSR, which should include the extra CO_2 emissions from non-operation activities of HSR less the avoided emissions from non-operation activities of the other modes due to traffic diversion to HSR. In other words, NE_{ct} can be written as

$$NE_{ct} = E_{ht}^{c} - \sum_{i} E_{it}^{c} \quad (5)$$

where E_{ht}^{c} is the actual CO_2 emissions from the non-operation activities of HSR in period t, and E_{it}^{c} is the avoided CO_2 emissions in this period as fewer infrastructure expansion projects are needed for transportation mode i in the "with HSR" scenario than the "without HSR" scenario. However, most existing studies only pay attention to the first component of Equation (5) with very little discussion on the second component. Here, another fundamental variable that needs to be taken into account is the lifespan or lifetime, which can be quite heterogeneous across different components of the non-operation activities within a transport mode and across different modes. In terms of different non-operation components, construction of infrastructures (e.g., airports, highways, HSR stations and tracks) only occurs once before the operation, but vehicle manufacturing can occur several times during the whole life cycle of the infrastructure. In terms of different transport modes, airports arguably have the shortest infrastructure lifespan, i.e., runways and terminals must be repaired and replaced on a much shorter time span than railway tracks and stations (especially in the OSR case). Highway infrastructure falls between these two extremes. This heterogeneity requires the net emissions to be annualized, which are obtained by evenly allocating generated emissions across the lifespan of the infrastructure and vehicles.

The net emissions throughout the life cycle of the HSR infrastructure are the sum of NE_{3t} across all the time, t, from the completion of the construction to the end of the lifespan. That is, at the end of the lifespan of the infrastructure, the life-cycle net CO2 emissions, denoted as NE, can be written as:

$$NE = \sum_{t} NE_{3t} \quad (6)$$

From the above discussion, we can see that Equation (1) is a component of Equation (2), which is in turn a component of Equation (4). This means that the first level of research can be treated as a component of the second level of research, which can itself be considered as a component of the third level of research. In order to better illustrate the inter-relationships among the three levels of research, we have presented their logical connections in Figure 2.

Insert Figure 2 about here

3. First Level: CO_2 Emission Rates

The first level of relevant research is to compare the amount of CO_2 or CO_2-equivalent (CO_2-eq, defined below) generated by different transportation modes to move one passenger for a certain distance. The unit of the analytical outcomes of such studies is usually or can be converted to grams of CO_2 per passenger-kilometer (g/pkm). Some papers, such as Kamga and Yazici (2014), only provide qualitative discussion regarding how building an HSR system may help to shift travelers away from cars and planes, thus creating a positive impact on the environment. Others adopt quantitative methods to generate more concrete assessments of such comparison.

Two groups of studies can be categorized into this camp. The first group only investigates the CO_2 emission rates e_h and e_i, without getting into the discussion of the diverted traffic component, Q_i^D, in Equation (1). For example, Levinson et al. (1999) consider air pollution as part of the social cost and compare the full costs of air transport and HSR for the California Corridor, which connects San Francisco and Los Angeles. They find that although the air pollution cost of HSR is negligible compared with the \$0.0009 per passenger-kilometer cost of air transport, overall the full cost of air transport is substantially less than that of HSR. However, the paper uses a different unit and doesn't present how the numbers have been calculated, making it very hard to compare its results with those from other studies. Janic (2003a) evaluates the differences between HSR and air transport in terms of their environmental impacts, concluding that significant environmental benefits could be achieved by substituting air traffic with HSR in the European Union (EU). Givoni (2007) adopts a seat-for-seat comparison for the London-Paris route and concludes that the substitution of aircraft capacity with HSR capacity indeed benefits the environment. This paper also investigates the CO_2 equivalent (CO_2-eq) emissions, which includes not only CO_2, but also CH_4 and N_2O emissions. The following equation is adopted to calculate the CO_2-eq according to IPCC's definition (IPCC, 2014):

$$CO_2 - eq = CO_2 + 28 * CH_4 + 265 * N_4O \quad (7)$$

Later studies go beyond the limitation only to compare the emission rates of HSR and air transport. Borken-Kleefeld et al. (2013) compare the CO_2 emissions of long-distance car travel with coach, train, and air trips. They conclude that factors such as vehicle efficiency, occupancy, and the carbon intensity of fuel all play a role in the comparison. But whether to take into account the short-lived climate forcers (including ozone precursors NOx, VOC, CO; aerosols such as BC, OC, SO_2; as well as aviation-induced cirrus clouds and contrails) can really change the assessment.

The second group of studies are also concerned about the CO_2 emission rates of different modes, but they also assume one or a few specific scenarios of traffic diversion from other modes to HSR. This allows them to draw conclusions about the total CO_2 emission effects of new/proposed HSR projects. For example, Jamin et al. (2004) predict the environmental impacts of substituting short-haul air traffic with HSR service in some U.S. corridors. They assume a specific partial substitution rate (2/3 air traffic + 1/3 HSR traffic) and conclude that the national emissions reduction would be only in the order of 1%, but the emission reduction on a local level may be significant. Robertson (2013) analyzes the reduction of CO2 emissions between 2010 and 2030 due to a modal shift from air travel to HSR in the Sydney-Melbourne market. He assumes a 50/50 modal shift and estimates that an annual emissions reduction of approximately 14% could be achieved. Prussi and Lonza (2018) carry out the study further by considering more than one scenario (0, 5%, and 25% of modal shift). They investigate seven European routes and find that with an annual passenger increase of 3.5%, shifting 5% and 25% of this increment from air transport to HSR lead to GHG savings of 4% and 20%, respectively.

The first level of research generally suggests that a shift from other transport modes to HSR service reduces environmental footprints, although they may differ in terms of how big this reduction can be.[5] This conclusion depends on many different factors, such as the types of vehicles operated by different modes, their load factors, the environment/purpose of the transport service, the distance of the OD market, and the carbon intensity of the energy sources for the transport modes. In the following Table 2, we summarize the values of the CO_2 emission rates obtained by different studies on this level for a clear comparison. It should be noted that in some studies, the emission rates are not directly given and are inferred and calculated by the authors.

Insert Table 2 about here

From Table 2, we can see that there is a large variety in the CO_2 emission rates, due to the fact that the reviewed papers in Table 2 all look at specific cases, which are distinctive from other cases due to their specific features. However, the magnitudes of these values are largely consistent within modes, suggesting the robustness of the results. An interesting observation of Table 2 is that other than Borken-Kleefeld et al. (2013), there is no study directly comparing the CO_2 emission rates of HSR and OSR. This is likely due to the fact that the power sources of HSR and OSR, a major determinant of the CO_2 emission rates, are usually the same within a particular country/market. Borken-Kleefeld et al. (2013) adopt a different approach by considering that HSR is powered by electricity while OSR is powered by diesel traction. This point can be clearly illustrated by

[5] Only one study, Hagedorn and Sieg (2019), concludes that coaches have lower per-passenger carbon emissions than HSR. The paper argues that the approach adopted by most studies, i.e., comparing emissions of various transportation modes in the same city-pair market or within the same distance, may not be suitable for leisure travelers as they decide where to travel and hence the travel distance based on a fixed "full price" budget that consists of the ticket price and time cost of the journey. Following this rationale, as HSR's ticket price reduces and its speed increases, the leisure trip distance of HSR increases, which can reduce the advantage of HSR over other road modes in terms of per-passenger carbon emissions. Unfortunately, also due to the different methodological logic adopted, the results of Hagedorn and Sieg (2019) cannot be compared with those of other studies.

referring to the study of Baumeister (2019), which assesses the per passenger CO_2-eq emissions of trains with the maximum speed at 200-220 km/hr (which by the UIC definition, is OSR instead of HSR), cars, and coaches, for 16 city-pair markets linking to Helsinki Airport in Finland. Since there is no HSR in Finland, and the Finnish OSR is also powered by electricity, it should have a similar carbon footprint with HSR (although higher due to higher speed), which is confirmed by a cross comparison between this and the other studies in Table 2. This further shows that the boundary between HSR and OSR is not as simple and straightforward as that between HSR and other transport modes, a point we noted earlier.

4. Second Level: CO_2 Emissions from Operations

A review of the relevant literature suggests a significant imbalance among studies on the interactions between HSR and other transport modes, with air transport taking the lion's share. This is likely due to the fact that air transport is widely considered to be the transport mode that has been affected the most by the introduction of HSR. Many studies have investigated the interactions between air transport and HSR service. In fact, the traffic implications of air-HSR interactions constitute a major literature stream in itself, and have thus been extensively discussed by review papers (Givoni and Dobruszkes, 2013; Sun et al., 2017; Zhang et al., 2019). Therefore, we choose not to repeat such a review in this paper. Instead, we focus on the studies that explicitly consider the impacts of the air-HSR interactions on the environment, which will be presented in Section 4.1. Different from air transport, the traffic implications of HSR's interactions with road transport and OSR draw much less attention from the literature, and as a result, no systematic review of studies has attempted to investigate such implications. Besides, there is a lack of existing studies on the second and the third levels of investigation as laid out in Section 2. Therefore, in Section 4.2, we will focus on the studies that analyze the traffic allocation between HSR and road transport as well as OSR.

4.1 CO_2 Emission Implications of HSR-Air Interactions

As pointed out by Woodburn et al. (2013), there is tremendous value in comparing the environmental impacts of air and HSR infrastructure. Government and industry reports also advocate the substitution of air transport with HSR service as a promising way to achieve reduction of greenhouse gases (GHGs) emissions (e.g., EC, 2011; TRB, 2013). As the environmental assessment of HSR-air substitution heavily relies on passengers' modal shift from air transport to HSR, more recent studies treat modal shift due to HSR-air substitution as endogenous. Compared with exogenous traffic analysis, these studies are able to obtain a more accurate assessment and capture more sophisticated market impacts of HSR-air competition due to the strategic interactions between the transport operators.[6] In particular, the introduction of HSR may lead to an expansion of the market (i.e., induced demand), causing unfavorable environmental consequences. In our conceptual framework, such an expansion of market is represented by Q_h^G and Q_i^G in Equation (2). Some studies only discuss these effects qualitatively. For example, Givoni and Banister (2006) point out that when air transport and HSR collaborate and the freed-up airport runway capacity is used to satisfy more demand, there may not be environmental gain from such complementarity. This is a similar mechanism as the one suggested by Cornet et al. (2018) and Givoni et al. (2012).

[6] Some studies point to this direction without formal analysis. For example, when assessing the CO2 emission implications of UK's HS2 project, Cornet et al. (2018) qualitatively point out that mode shift from air to HSR can indeed reduce carbon emissions, but that conclusion depends on how the freed-up capacity at airports is being used.

Givoni and Dobruszkes (2013) also reiterate this point with more evidence. In a study of the Australian market, Bukovac and Douglas (2019) estimate air/HSR market share using the European experiences, suggesting that the environmental gains from the construction of HSR can easily be reversed by traffic demand stimulation.

Other studies adopt a more quantitative analysis. Interestingly, these studies use different methods to analyze the modal shift. Generally speaking, three types of methods have been adopted to obtain an endogenous allocation of traffic among modes. The first type is discrete choice models, which assume certain ways of traffic split given the utility levels of passengers when the attributes of transport services are given. Sonnenberg (2010) adopts such a model developed by the Volpe Center (Volpe Center, 2008) to estimate modal shift and finds that a substantial shift from air to HSR only happens when HSR adopts faster speed. He also points out that potential CO_2 emissions savings are closely related to the load factor of HSR. Zanin et al. (2012) use a probabilistic model to account for the uncertainty in passengers' individual behaviors, and investigate the environmental impact of air-HSR complementarity in Madrid Barajas Airport, concluding that a 10% reduction in all emissions has been achieved. Dalkic et al. (2017) use an HSR user survey to examine two HSR lines in Turkey (Ankara-Eskisehir and Ankara-Konya). They show that substituting alternative transport modes including air transport with HSR service has caused a total reduction of 24.3 KT CO_2, and may even result in a reduction of 452.7 KT CO_2 in 2023.

The second type of method is counterfactual analysis. Studies adopting such methods are all ex-post research after the entry of HSR. Through estimating the counterfactual scenario when HSR does not exist, these studies can conclude how traffic allocation was achieved among modes. Li and Loo (2017) examine China's railway development and its impact on air transport from 1993 to 2012. They conclude that the shift from air to rail contributes to a net reduction of 2.83 million tons of carbon emissions, which is about 6.9% of emissions from these two transport modes in 2010. Wang et al. (2019) compare the routes that saw a direct entry of HSR during the sample period (2000-2015) with those that didn't face HSR entry. They estimate that HSR generated a cumulative net saving of between 1.76 and 2.76 million tons of CO_2 through substitution for air transport.

The third type of method is game-theoretical modeling, which takes into account the competitive dynamics between transport modes and has the potential to endogenize all transport service attributes. For example, Socorro and Viecens (2013) use theoretical model derivation to confirm the negative environmental impact of air-HSR complementarity pointed out by Givoni and Banister (2006). D'Alfonso et al. (2015, 2016) use game theory models to show that introducing HSR may lead to a net negative impact on the environment due to the induced demand. In particular, there exists an intricate trade-off between a traffic substitution effect and a traffic generation effect. Xu et al. (2020) find that whether the HSR operator and the airline engage in Cournot competition or a Bertrand competition matters to the strategic corporate social responsibility (CSR, with environmental impact as one criterion) of the HSR operator. Jiang et al. (2021) explicitly consider service frequency as a strategic decision for both the airline and the HSR operator, as frequency is closely related to the vehicle size of the transport modes, which has major implications on the environmental consequences of HSR-air complementarity/cooperation. They conclude that the overall environmental assessment depends on the market conditions of both the long-haul route and the short-haul route involved in the intermodal cooperation.

A comparison of the three methods shows that they are focusing on different aspects. The discrete choice models pay attention to the demand side of modal split. However, the supply side interactions between the transport operators are not the focus of these studies. The counterfactual analysis provides information regarding the net change of traffic for certain transport mode, but they usually do not differentiate the generated traffic with the diverted traffic, as we discuss in Equation (2). The game-theoretical models can take into account the detailed interactions between transport modes and can also distinguish the generated traffic with the diverted traffic, but so far, studies adopting such methods are all pure theoretical exercises as calibrating these models to generate meaningful empirical outcomes is very challenging. In particular, strong assumptions usually need to be adopted to enable the models to be easily and directly fit into a real-life context/data. One immediate research opportunity from this group of studies is to further develop the game-theoretical models to be applied to estimate real-life modal split and CO_2 emission impacts. The comparisons between the three methods are summarized in Table 3.

Insert Table 3 about here

The above-discussed studies all focus on the passenger side only. However, passengers only account for a portion of the traffic for most transport modes. In particular, although HSR is still mainly a passenger transport mode,[7] air, road and OSR all have substantial cargo operations, which also contribute to their total CO_2 emissions. It is plausible, at least logically, that by affecting the passenger business of another transport mode, HSR can also indirectly affect its cargo business. Cai et al. (2021) prove, theoretically, that when airlines use aircraft belly to transport cargo and the belly capacity is limited, introducing HSR as a competitor in the passenger sector would reduce

[7] China has successfully developed freight-dedicated high-speed trains, so the fact that HSR is mainly a passenger-only transport mode may be changed in the near future, but this remains to be seen (e.g., Cai et al., 2021).

air traffic in both passenger and cargo sectors. Chen and Jiang (2020) empirically show that the entry of HSR services reduces the belly-hold cargo volumes and flight frequencies, with the strongest impacts observed in the medium-haul markets. At the same time, the cargo volumes and flight frequencies of freighter cargo increase, albeit not able to fully compensate for the loss of belly cargo capacity. These two papers are the only published studies that attempt to find out the intricate impact of HSR on air cargo, and neither has specifically investigated the emission consequence. This is clearly another under-researched area that requires some immediate attention for studying the complete CO_2 emission impacts of HSR operations due to modal interactions.

4.2 Traffic Reallocation Implications of the HSR-Road and the HSR-OSR Interactions

4.2.1 HSR-Road

In general, the impacts of HSR on cars and coaches vary significantly across markets and can be quite strong in certain cases. As summarized in a comprehensive review conducted by Givoni and Dobruszkes (2013), among various inter-city markets in Europe, the percentage of HSR demand that comes from car users can be as low as 7% and as high as 31% and that of which comes from coach users range from less than 1% to 12%. The market share of cars dropped more severely than coaches after the introduction of HSR, because coaches play a much smaller role in inter-city passenger transport than private cars in the case of Europe. For example, the share of cars dropped from 61% to 43% while the share of coaches dropped from 9% to 5% after the entry of HSR in the Paris–Brussels market (312 km). However, the impact can be stronger on coaches than cars in certain markets where passengers have a different travel behavior before the entry of HSR. For example, in Taiwan, coaches are more important than cars for inter-city travel. Thus, after the entry of HSR to the 345 km Taipei–Kaohsiung route, the share of cars dropped from 28.2% to 20.6% while the share of coaches dropped from 35.3% to 22.3%. Similarly, on the 308 km Taipei–Tainan route, cars dropped from 24.3% to 20.7% while coaches dropped from 55.3% to 46.1%. The lesson is that if cars have a much higher per-passenger emission rate than coaches in general, HSR can be more effective in reducing carbon emissions by diverting traffic from road modes in societies where cars dominate inter-city road transport. A recent study by Lin et al. (2021) is the first academic paper to analyze how HSR affects not only passenger road traffic but also cargo road traffic. In particular, they find that the HSR connection is associated with a substantial reduction in passenger vehicle number (20.5 log-point) and a smaller but still significant reduction in freight vehicle number (15.7 log-point) on highways but not ordinary national roads in China. They conjecture that this is due to the fact that HSR can draw passengers away from conventional railways (i.e., OSR), leading to a significant increase of freight capacity on these lines, which would cause the shift of highway goods transport to the conventional railway.[8] Based on this assumption, they further calculate the corresponding emission effects and conclude that an annual reduction of 14.758 million tons of CO2 equivalent of greenhouse gas (GHG) emissions (i.e., 1.75% of GHG emissions in China's transportation sector) has been achieved. This research is very timely as it specifically points out an important mechanism for HSR operations to affect CO_2 emission in the transport sector.

[8] Chen et al. (2021) find, in the case of Beijing-Shanghai HSR line that started its service on June 30, 2011, that from 2011 to 2017, the diverted traffic from OSR to HSR accounted for 41.55% of the Beijing-Shanghai HSR's passenger volume. Would the freed OSR capacity from passengers be utilized for freight transport? Chen et al. (2021) find that the freight traffic volume of the Beijing-Shanghai OSR had not increased much during the 2011-2017 period. On the other hand, Cheng and Chen (2021), after examining the spatial and temporal variations of transport capacities of HSR and OSR systems in China, provide a clear-cut positive answer to the question.

In addition to ex-post observation of actual traffic or modal share changes before and after the launch of HSR services, a number of studies build discrete choice models with survey data to understand the influential factors of modal shift from road to HSR, such as travel time, travel cost, service frequency, trip distance, trip purpose, and group size. González-Savignat (2004) focuses on the factors causing car users to shift to HSR in Spain. He found that car users' shift to HSR mainly depends on both modes' travel cost and travel time, while the impact of HSR frequency is smaller. While business travelers are more travel time sensitive, leisure travelers are more travel cost sensitive. More interestingly, leisure travelers traveling in groups are especially sensitive to HSR travel cost than those traveling alone and both types of travelers have a similar level of sensitivity to car travel cost, because a reduction in HSR ticket price will generate larger cost savings for a group of travelers than one single traveler. In terms of distance, short-distance travelers are more sensitive to HSR's attributes than long-distance travelers. A study in South Korea suggests that the probability of choosing an intercity coach is more sensitive to HSR in-vehicle time and HSR ticket price than the probability of choosing cars (Lee et al, 2004). Based on surveys conducted by the Ministry of Land, Infrastructure, Transport and Tourism of Japan, Yashiro and Kato (2020) found that an improvement in the intermodal connection between HSR and interregional buses that mainly connect to cities without HSR stations can also effectively shift car and conventional rail users to rail-bus intermodal services.

Combining the findings in the above studies based on discrete choice models with the discussion about the per-passenger GHG emissions, one may conclude that HSR's effectiveness in reducing GHG emissions by diverting road traffic can be largely affected by individual routes' characteristics, the ticket price it charges and the targeting market segment. In particular, HSR can effectively reduce GHG emissions if it is substantially faster than road transport and hence can attract a large number of business travelers who tend to drive alone and hence emit more when traveling with cars. Attracting road users to HSR by reducing HSR ticket prices may not be beneficial to the environment because HSR price reduction is more attractive to group travelers on leisure trips. These travelers may in fact generate lower per-passenger emissions when they travel together in one car. In such cases, to prevent high-occupancy cars from shifting to HSR, HSR discount needs to be coupled with extra incentives to increase cars' load factor.

The generation of new travel demand in the form of HSR traffic after the entry of HSR has been well documented in the literature (refer to Givoni and Dobruszkes (2013) for a review), and hence emissions of induced HSR traffic has been widely included in the discussion about HSR's environmental impact. However, an increase in road traffic after the inauguration of HSR services is also reported in some cases. For example, a study conducted by the European Commission found that after the launch of HSR, the Madrid-Seville route saw a 23% increase in car passengers (Givoni and Dobruszkes, 2013). Borsati and Albalate (2020) also found with a difference-in-difference model that HSR expansion is positively associated with light vehicle-km traveled on the adjacent highway sectors. This finding implies that HSR might have difficulty in reducing car traffic. The generation of new road traffic after the launch of HSR has not been thoroughly discussed in the literature. To our knowledge, Borsati and Albalate (2020) and He and Li (2018) are the only papers that examine the impact of HSR on highway traffic using statistical models. The former is based on data taken for each highway sector in Italy, while the latter is based on aggregated provincial-level data in China.

According to Borsati and Albalate (2020), there can be several reasons behind the induced road traffic. First, HSR has a positive impact on surrounding economic activities, leading to an increase in travel demand. Second, as some conventional train users shift to HSR, the supply of conventional train services reduces, leading to increased car dependency for commuting travelers between intermediate stops of conventional train services. Finally, HSR and car may interact in a complementary manner, as the former links two endpoint cities while the latter may enter or exit the motorway at several locations along the motorway. While these channels of HSR impacts on road traffic have never been explicitly tested in the literature, He and Li's (2018) regression analysis seems partially consistent with the first channel proposed by Borsati and Albalate (2020). In detail, He and Li (2018) found that regions with large population sizes may experience an increase in highway traffic after the introduction of HSR. However, regions with higher gross regional products tend to experience more substantial highway traffic reduction after the introduction of HSR. Using data collected in Japan, Otsuka (2020) proposes a nonlinear relationship between per capita energy consumption of passenger cars and inter-regional transportation networks. Admittedly, it becomes more convenient to use cars as the transportation network improves initially, but once the improvement reaches a certain threshold, the energy consumption of cars eventually reduces due to modal shift after the introduction of faster modes, such as HSR, into the transportation network. In the long run, a 1% improvement in inter-regional transportation will lead to over 1.5% reduction in per capita energy consumption of cars.

4.2.2 HSR-OSR

OSR has been used as an important transport mode for medium- and long-haul travels. HSR provides high-quality substitutes for conventional railways and long-distance coach services (Li et al., 2020). For instance, the China Statistical Yearbook (2018) shows that during the 2007-2017 period, the modal share of coaches and conventional railways for intercity passenger travel in China dropped roughly from 85% to 55%, whilst the share of airplanes and HSR grew from around 15% to 45%.

In most cases, the majority of HSR passengers come from those who used conventional railways before (Givoni and Dobruszkes, 2013). Givoni (2006) reviews the operating characteristics and design of HSR and argues that HSR is to replace conventional railway services on routes that require higher capacity and less travel time. The reviews by Givoni (2006) and Givoni and Dobruszkes (2013) show that the demand for HSR passengers is about 10–20% induced demand and the rest is dominated by mode substitution, which is mainly from the conventional railway. In other words, many passengers shift away from conventional railways to parallel HSR. In most situations, substitution from air and road transport is generally more modest. For example, Segal (2006) finds that after the entry of HSR, 47% and 12% of HSR passengers on the Paris–Bruxelles–Cologne/Amsterdam route and the London–Paris/Lille/Brussels route were conventional railway passengers, respectively. Cascetta et al. (2011) show that 69% of HSR demand on the Rome–Naples route is from conventional railways in 2007. On the Osaka–Hakata HSR line, Okabe (1979) finds that 55% of HSR passengers are shifted from conventional railways. Suh et al. (2005) examine the Korean case and show that 56% of HSR demand comes from conventional railways. In the Chinese market, Bullock et al. (2012) find that on the Wuhan-Guangzhou route, about half of HSR passengers are from the parallel conventional railway service. Cheng and Chen (2021) further conclude that a service cut in conventional passenger rail due to the substitutional effect from HSR contributes to an increase in the capacity of freight rail. They have a similar conjecture as Lin et al. (2021) that this additional freight moved by rail is diverted from road transport. Although these two recent studies (i.e., Cheng and Chen (2021) and Lin et al. (2021)) are only logically (but not empirically) connected, and Cheng and Chen (2021) never attempt to analyze emissions specifically; they, as well as Chen and Jiang (2020) and Cai et al. (2021) on the air side, collectively raise the awareness that a comprehensive evaluation of HSR's impacts on transport emissions is nowhere to find without explicitly considering the cargo business.

Apparently, the research gap and opportunity for the second level of research involving HSR-road and HSR-OSR interactions are very obvious. In particular, specific analysis regarding the CO_2 emission implications of such interactions should be implemented. Besides, more detailed and intricate analyses regarding the cargo business should also be further developed.

5. Third Level: Life-Cycle Assessment

Due to its comprehensiveness, LCA has become a very popular methodology in evaluating the environmental impacts of various projects. LCA in the context of transportation may consist of some or all elements illustrated in Figure 3. From Figure 3 we can see that traffic assessment is only a subset of LCA, typically covering the active operations of vehicle components only. Therefore, LCA is supposed to give a more thorough evaluation of transport projects than traffic assessment. However, due to the higher level of complexity, existing LCA studies have to compromise in other important aspects. In particular, no LCA has ever treated modal split as endogenous and obtained rigorous assessment of HSR projects' impacts on traffic of different transport modes.[9] Besides, no LCA study has specifically identified and evaluated the potential impact of intermodal complementarity.

Insert Figure 3 about here

As shown in Figure 3, there exist three possible components for LCA. The first component is whether the environmental benefit from the operations of HSR can compensate for emissions from the infrastructure construction. This component is normally the starting point of LCA, with most studies taking it into account in the analysis. The second component is the manufacturing, maintenance, and operations of the vehicles. This component should be separated into two parts. The operation of the vehicles is always at the center of research, as it appears in both the first and the second levels of studies. However, the discussion regarding the manufacturing and the maintenance of the vehicles appears later in the literature compared with those of infrastructure and draws less attention than the other two components, possibly due to its smaller impact on the analysis results. The last component is the sources and mix of energy that powers the transport modes.[10] Earlier studies tend to ignore the CO_2 emission due to the production of energy, but recent research has realized its importance and potential for future policy and development guidance.

It should be noted that not all the HSR projects could be directly compared from an LCA perspective, as there are many differences in construction/maintenance depending on topography and weather conditions. Besides, it is well known that energy consumption is correlated to the

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[9] Some studies are able to combine endogenous traffic analysis and certain LCA elements. For example, Ha et al. (2011) use a panel data set from 1999 to 2007 to estimate the social efficiency of the air transport sector and three railway companies in Japan, incorporating CO_2 emissions from not only the transport service provision but also the infrastructure construction.

[10] There also exist studies focusing only on the energy consumption comparisons between HSR and air transport without going one step further to calculate the corresponding environmental implications. For example, Dalla Chiara et al. (2017) quantify and compare the energy consumption of air transport and HSR, suggesting that HSR is a better option regarding the environmental impacts.

square of the speed. And as we can see from Table 1, not all the HSR services have the same speed. Therefore, it is not the purpose of this section to compare LCA results across different studies. Instead, we try to compare the coverages of different relevant LCA studies in order to obtain insights regarding how future research down this line should proceed. Table 4 summarizes which LCA components have been covered by specific studies.[11]

Insert Table 4 about here

Kato et al. (2005) conduct likely the first real LCA for HSR-air substitution. They evaluate the change of life-cycle carbon dioxide (LC- CO_2) emissions due to a shift from existing inter-regional transport modes including air transport to the Maglev. Various market factors can lead to different conclusions regarding whether the HSR substitution of air travel really benefits the environment. Åkerman (2011) is optimistic in his LCA of the Swedish proposed HSR track Europabanan. He suggests that the introduction of the HSR line can reduce the need for road and airport capacities, leading to a more favorable environmental assessment. Using the California corridor for analysis, Chester and Horvath (2010; 2012) point out that while HSR is potentially the lowest energy-consuming and GHG-emitting transport mode, a sustained high occupancy rate/load factor is necessary for such potential to be fully realized. Besides, the life-cycle approach will add 77~116% additional GHG emissions to HSR, but only 38~54% to cars. Westin and Kågeson (2012) analyze the climate benefit from the new HSR project by using the Monte Carlo simulation. They argue that the degree of air traffic substitution is crucial, and we need at least 10 million annual HSR

[11] It is worth noting that there exist studies that technically are not LCA but incorporate some LCA elements. For example, Janic (2003b) builds a multicriteria evaluation framework to compare HSR, Transrapid Maglev, and Air Passenger Transport in Europe. Environmental factors under consideration include air pollution, noise, and land use. In other words, some life-cycle factors have been incorporated, although it is technically not a rigorous LCA study. Prussi et al. (2019) consider the potential for airlines to utilize biomass derived fuels (BDF) in the emission calculations for the London–Paris and the Frankfurt–Amsterdam routes. They conclude that BDF is yet a cost-efficient solution for the airline to catch up with HSR in terms of CO_2 emissions.

trips to balance the embedded construction emissions. Miyoshi and Givoni (2013) investigate the London-Manchester route and reach a similar conclusion. They suggest that the introduction of HSR has limited potential in CO_2 reduction as the modal shift from air (and road) to HSR is projected to be relatively small on that route. Matute and Chester (2015) study the California HSR (CAHSR) project and conclude that it would be considered a cost-effective way to reduce GHG emissions only when the diversion from car and airplane is taken into consideration. Krishnan et al. (2015) provide an integrated analysis for the U.S. transportation and electricity network, investigating the impact of HSR investments on inter-state passenger transport, fuel and electricity consumption, as well as CO_2 emissions. They suggest that a 30% HSR penetration can lead to a gasoline and jet fuel consumption reduction of up to 34%, and a CO_2 emissions reduction of about 0.8 billion short tons. Yue et al. (2015) employ the China-specific life-cycle inventory database to examine the LCA of the Beijing-Shanghai HSR. The authors conclude that the environmental impact of the Chinese HSR system is larger than that of the conventional rail system, but less than those of the road and the air transportation systems. Based on a simplified LCA of a new HSR in Spain, Hoyos et al. (2016) show that HSR consumes more energy and emits more CO_2 than conventional rail. Robertson (2016) points out that the inclusion of the linehaul infrastructure increases the CO_2 load associated with HSR, but HSR still exhibits substantial advantages over air transport. The author estimates that in 2056, there can be an 18% reduction of annual LC CO_2 emission compared to the air travel only scenario, totally 0.37 million tons (Mt). Bueno et al. (2017) analyze the contribution of the HSR project in the Basque Country, Spain. They calculate the CO_2 emissions from the construction and maintenance of the infrastructure to be at 2,71 Mt CO_2, which would require at least 55 years of service of the HSR to achieve CO_2 reduction. Robertson (2018) extends Robertson (2016) by considering a range of renewable energy technologies. He suggests that the annual LC CO_2 emissions can be reduced by 56-69% with a 60% modal shift from air to HSR and the adoption of renewable energy technologies. All the above-discussed papers are only concerned about the first component, E_h^c, in Equation (5). Chen et al. (2021) is the only paper that has discussed the second component in the equation. In particular, they consider the effects of avoided expansion of infrastructure and manufacturing of vehicles caused by traffic diversion on the Beijing-Shanghai corridor. They find that the environmental effect of avoided infrastructure expansion is insignificant compared with the construction of an HSR infrastructure, but the avoided productions of vehicles can offset a larger share of emissions from the manufacturing of the rolling stocks of HSR.

To conclude, LCA is generally less optimistic about the environmental benefits of substituting air transport with HSR service. But a review of the relevant studies classified as our third level of research has pointed out that a lot more can still be done in this area. First, there should be more analysis following the setting of Chen et al. (2021) and considering the avoided life-cycle emissions associated with infrastructure and vehicles due to traffic diversion. One common blind spot for the existing studies is that the infrastructure of the non-HSR transport modes is usually treated as static and unchanged. However, as suggested by Jiang and Li (2016), Wang et al. (2021), and Jiang and Wang (2021), HSR is not necessarily always the "new" transport mode. If other transport service providers, such as low-cost carriers, enter a market where HSR is already present, it would be more important to consider the second component in Equation (5) of our framework.[12] Second, the analysis regarding vehicle operations in the current LCA studies still lacks the

[12] In effect, Wang et al. (2021) provide an analytical examination of the effects of airline entry on, among others, HSR's service frequency, number of train stops and the train size.

intricacy that the second level of research has already shown. That should be another direction of future improvement for this line of research.

As discussed in Section 2, the lifespans of the infrastructure and the vehicles are critical in the LCA of different transport modes. However, this element is also less specified in the existing studies. In particular, strong assumptions are usually imposed without very solid justification. For example, many studies simply assume the same lifespan for all the infrastructure across different modes. This is likely due to a lack of relevant information. After all, there is no retired HSR infrastructure yet, making it very hard to come up with a specific number for its lifespan.

6. Concluding Remarks

In this paper, we provide a comprehensive review of existing studies on the environmental implications of interactions between HSR and other transportation modes, including air, road, and conventional rail. In particular, we conceptually classify the studies into three levels, with the first level focusing on the emission comparison between HSR and the other modes, the second level focusing on the emission implications due to HSR-induced traffic reallocation, and the third level focusing on the LCA. In between the first two levels of research, there is also a group of studies investigating the traffic implications of HSR-induced modal interactions, which, with the help of the first level of research, can implicitly lead to certain contributions towards the second level.

Upon reviewing this line of research, we can draw a few conclusions about the status quo of the literature. First off, the literature is still in a relatively premature state. Although there already exist some studies, many important factors and mechanisms haven’t been adequately considered. For example, cargo transportation has been largely ignored in the literature. However, the modal shift of freight from road to conventional rail (OSR), for which HSR capacity is an essential pre-condition, could well produce more significant CO_2 impacts than the ones estimated by existing studies. So far only one recent paper has attempted to carry out such investigation, with many more needed to come so as to fill the void. In the meantime, certain limitations and analytical deficiencies have also been accumulated in the existing studies. Clearly identifying these deficiencies is critical for the implementation of future analysis that aims to be more effective and complete.

Second, there is a major imbalance between the studies of different transport modes. In particular, most of the existing papers on the HSR-induced modal shift and the corresponding environmental consequences focus on air transport, while road transport and conventional rail receive much lower attention. Specifically, while studies on air transport have covered all three levels of research, those on road transport and conventional rail mainly concentrate on the first level. Only a handful of papers have considered the HSR-induced traffic implications for road transport and conventional rail, and studies taking such discussion one step further to obtain environmental analysis are yet to be done. This imbalance is understandable, as among the three transport modes, air transport is affected the most by HSR. However, as revealed by the few existing studies, the impacts of HSR-road transport and HSR-conventional railway interactions are definitely not negligible and deserve deeper and more comprehensive investigations.

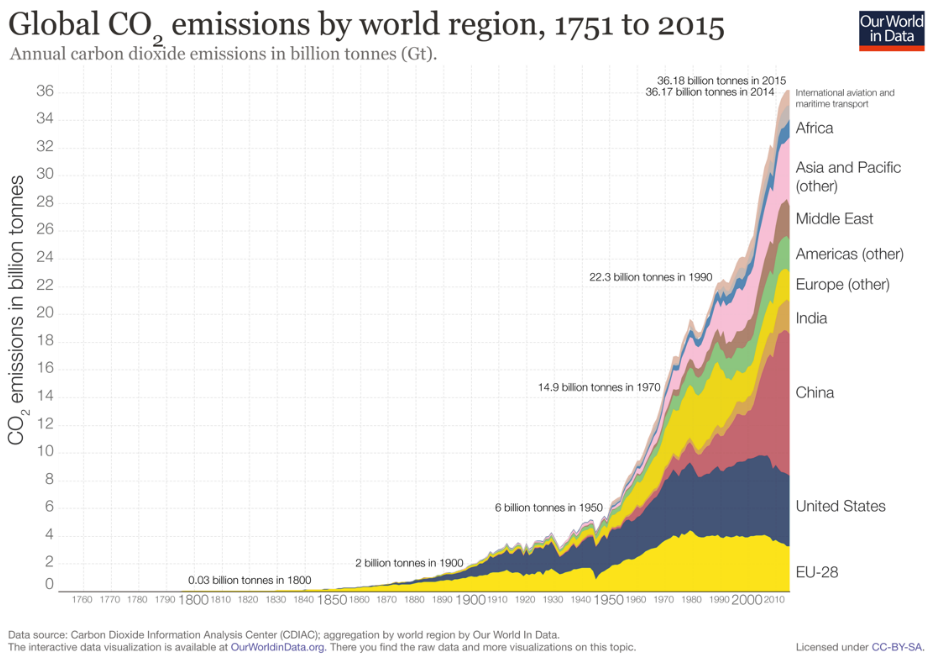
Third, almost all the studies reviewed in this paper have a unified objective, which is to evaluate whether the introduction and the development of HSR would bring environmental benefits to society. However, the answer to this question depends on the methodology applied in the research and the transport mode in comparison. In particular, the three levels of research identified in Figure 2 may point to different conclusions. The first level tends to be favorable to the HSR projects, suggesting that the seat-for-seat or per-passenger emission of HSR is generally lower compared with the other modes, although many factors need to be taken into account in order to reach a more accurate comparison. The second level of research obtains more mixed results, especially when modal complementarity and HSR-induced traffic are considered. However, it is usually the third level of research that reaches the least favorable assessments for HSR projects, suggesting that the non-operational components of these projects are in general causing larger negative impacts on the environment. This difference in conclusions depending on the scope of the research has very important policy implications. In particular, in order to obtain the most comprehensive assessment of the environmental implications of HSR projects, LCA should be adopted as the main tool. And policy makers should thus be careful in claiming the environmental benefits of HSR projects in general, as it is far away from a universal reality that HSR is a more environmentally friendly transport mode than other alternatives. However, our literature review also suggests that current LCA frameworks fail to incorporate the intricate analysis of transport operations that have been presented in the lower-level research. In other words, future evaluation of HSR projects should probably combine the best features from all three levels of research so as to obtain a more accurate assessment.

Fourth, this review suggests that it is a very intricate research topic to study the modal shift due to HSR and its corresponding environmental consequences. Many factors need to be considered and analyzed. None of the reviewed studies are even close to covering all the critical aspects. In other words, all the conclusions drawn from the literature are likely partial and specific in nature. This is acceptable due to the different agendas of the research projects. However, this status quo also suggests that there is an imminent necessity to synthesize all the related studies and build a comprehensive framework for future usage. Such a framework would be very complicated, but it can be useful to provide a big picture and help assess the environmental implications of a proposed HSR project.

Finally, this review identifies some clear research opportunities that have not yet been fully explored. Apart from the ones indicated above, a more detailed analysis regarding how HSR affects cargo operations of other transport modes and the corresponding CO_2 emission implications should be carried out. Besides, the game-theoretical models should be further developed to be applied to estimate real-life modal split and CO_2 emission impacts in specific cases. Research involving the exact CO_2 emission implications of HSR-road and HSR-OSR interactions should also be implemented. Furthermore, there should be more LCA studies considering the avoided life-cycle emissions associated with infrastructure and vehicles due to traffic diversion, as well as the intricacies of modal interactions.

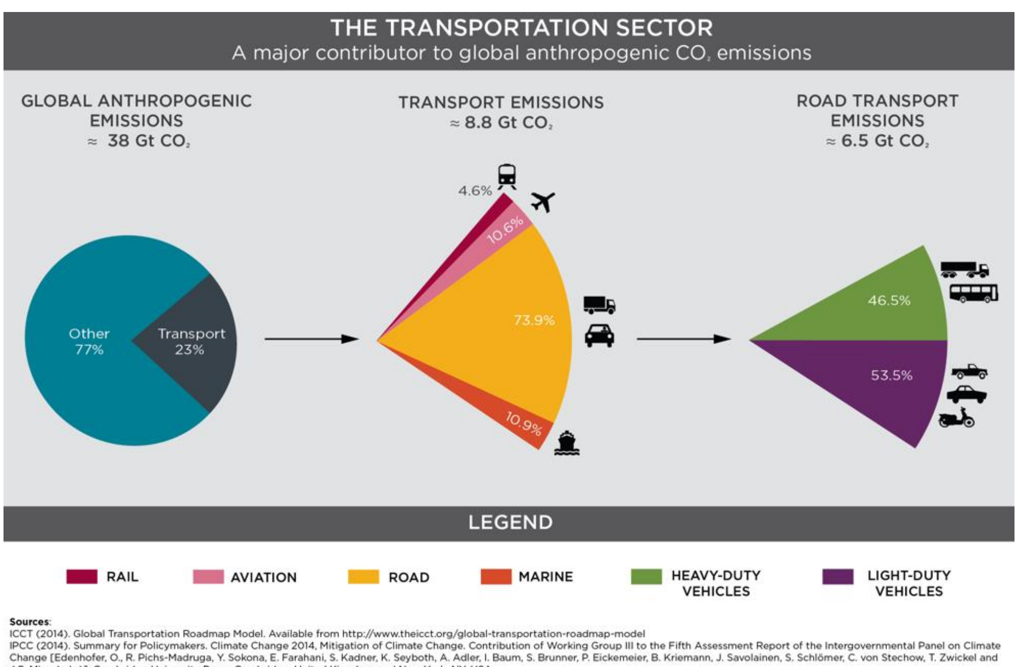
Figure 1: The Global CO_2 Emission Level and the Role of Transportation

(a) Global CO_2 Emission Level



Source: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

(b) Global CO_2 emission from Transportation



Source: https://theicct.org/blogs/staff/a-world-of-thoughts-on-phase-2

Figure 2: The Three Levels of Categorization for Studies on the CO_2 Emission Impacts of HSR's Interactions with Other Transport Modes

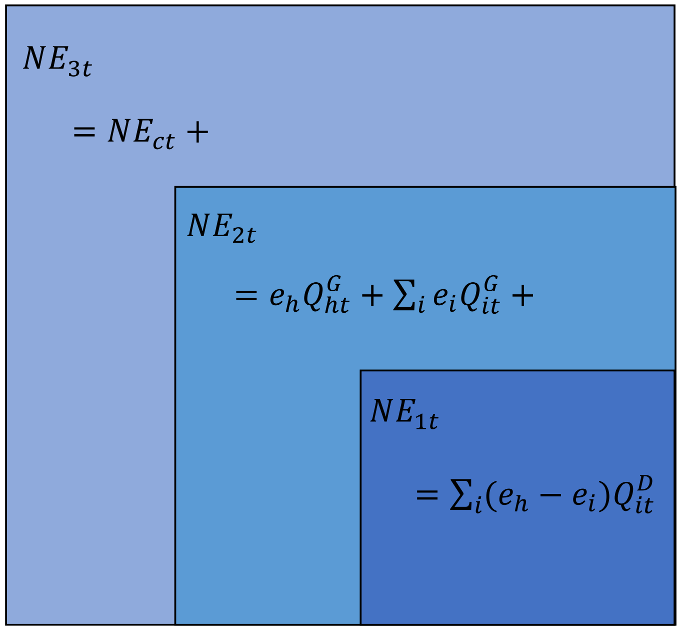


Figure 3: Elements of Transportation Projects' Life-Cycle Assessment

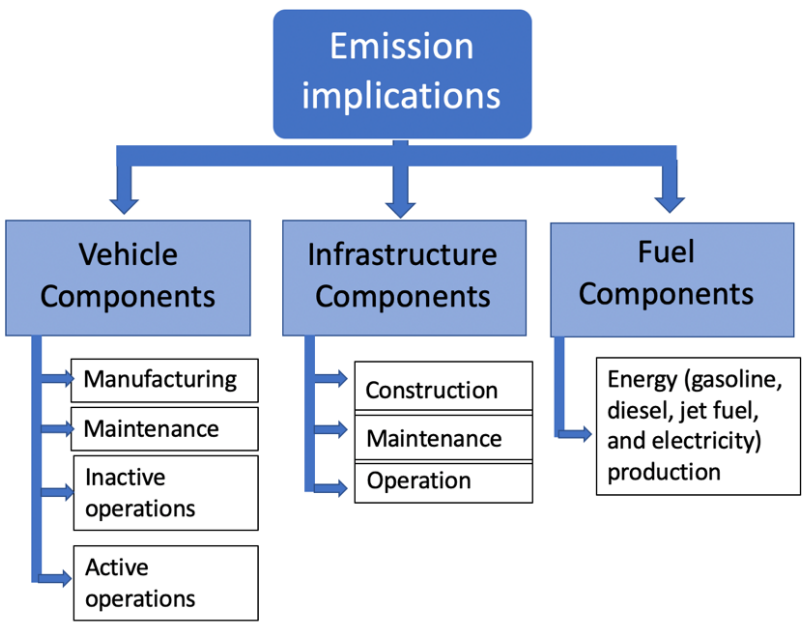


Table 1: Information of HSR lines in different countries/regions in 2018

Country/Region		Length of lines in operation (km)	Length of lines under construction (km)	Approved but not started construction	Max speed (km/h)
China	Mainland	26,869	10,738	1,268	350
	Taiwan	354	0	0	300
Spain		3,100	1,800	0	310
Japan		3,041	402	194	320
France		3,220	125	0	320
Germany		3,038	330	0	300
United Kingdom		1,377	230	320	300
South Korea		1,104	376	49	305
Italy		999	116	0	300
Turkey		802	1,208	1,127	300
Uzbekistan		600	0	0	250
Austria		352	208	0	250
Belgium		326	0	0	300
Netherlands		175	0	0	300
Switzerland		144	15	0	250
Luxembourg		142	0	0	320
Saudi Arabia		0	453	0	300

Thailand	0	0	615	300
Russia	0	0	770	250
Iran	0	0	1,351	300
Indonesia	0	0	712	250
India	0	0	508	250
Malaysia / Singapore	0	0	350	250
Israel	0	0	85	250
Portugal	0	0	550	250
Czech Republic	0	0	660	250
Greece	0	500	200	250
Hungary-Romania	0	0	460	250

Source: https://www.eesi.org/papers/view/fact-sheet-high-speed-rail-development-worldwide

Note: In this paper, we adopt the most accepted definition of HSR by the International Union of Railways (UIC), which requires the commercial speed to be higher than 250 km/h. With this definition, we have deleted some entries in the table.

Table 2: The CO_2 emission rates (g/pkm) of various transport modes identified by different studies

	e_h	e_a	e_{co}	e_{ca}	e_o
Janic (2003a)	4.011-27.515	99.8-153.9	NA	NA	NA
Jamin et al. (2004)*	22.18	105.83	NA	NA	NA
Givoni (2007)*	14.388 (14.494)**	85.032 (163.694)**	NA	NA	NA
Borken-Kleefeld et al. (2013)*	0***	85.33-135.47	17.14	25.5-54.8	26.25
Robertson (2013)****	45-55	80-90	NA	NA	NA
Prussi and Lonza (2018)	15-33.6	102-143	NA	NA	NA
Baumeister (2019)	N/A	128-188 (129.1-189.61)**	39 (39.47)**	69	4.59-9.35 (9.13-18.59)**

* The emission rates are not directly presented in the text or presented in different units in the original papers and converted to the g/pkm by the authors.

** The CO_2-eq emission rates are presented within the brackets.

*** This paper does not consider emissions from electricity generation.

**** Robertson (2013) only provides rough values of the emission rates in graphs.

Table 3: A comparison between three methods adopted in the second level of research

	Papers	Focus
Discrete Choice Models	Sonnenberg (2010); Zanin et al. (2012); Dalkic et al. (2017)	Demand side of modal split
Counterfactual Analysis	Li and Loo (2017); Wang et al. (2019)	Net change of traffic

Game Theoretical Models	Socorro and Viecens (2013); D'Alfonso et al. (2015, 2016); Xu et al. (2020); Jiang et al. (2021)	Strategic interactions between operators of transport modes

Table 4: Components of LCA covered by different studies

Paper	Infrastructure Components	Vehicle Components	Fuel Components
Kato et al. (2005)	✓	✓	
Åkerman (2011)	✓	✓	✓
Chester and Horvath (2012)	✓	✓	✓
Westin and Kågeson (2012)	✓	✓	✓
Miyoshi and Givoni (2013)	✓	✓	✓
Krishnan et al. (2015)		✓	✓
Matute and Chester (2015)	✓	✓	
Yue et al. (2015)	✓	✓	
Hoyos et al. (2016)	✓	✓	
Robertson (2016)	✓	✓	✓
Bueno et al. (2016)	✓	✓	
Robertson (2018)	✓	✓	✓
Kortazar et al. (2021)	✓	✓	
Chen et al. (2021)	✓	✓	

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