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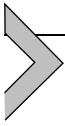
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# The environmental impact of high-speed rail

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## Abstract

This chapter presents a comprehensive literature review aimed at examining the environmental impacts of high-speed rail (HSR). The findings are organized into two frameworks: one addressing the environmental impact of HSR operations and another addressing the lifetime environmental impact of HSR investments. These frameworks illustrate the factors influencing the environmental impact of HSR and the mechanisms through which HSR affects the environment. Approximately 50 % of the studies assessing the lifetime environmental impact and 15 % of those focusing on the environmental effects of HSR operations conclude that the overall environmental impact of HSR is not positive. This is noteworthy since rail travel typically generates lower emissions per passenger kilometer than other transport modes, and policy-makers often consider HSR an environmentally friendly mode of transportation. Furthermore, HSR's environmental impact varies considerably based on several factors, including the economic and industrial characteristics of regions connected by HSR and the specific attributes of their existing transport systems. However, the review does not show any clear trends regarding the nature (positive or negative) and magnitude of the environmental impact associated with these factors. It highlights the importance of conducting thorough environmental evaluations on a case-by-case basis when considering HSR investment due to its environmental advantages.



## 1. Introduction

HSR is regarded as a vital element in achieving sustainable mobility. Due to its high energy efficiency, it is seen as more environmentally friendly than other modes, such as air and road transportation. Therefore, the European Union aims to double HSR traffic by 2030 and triple it by 2050 ([European Union Agency for Railways, 2024](#); [International Union of Railways \(UIC\), 2024](#)). Moreover, the HSR network is rapidly expanding worldwide, especially in China, because of its environmental benefits and its contribution to economic development (see [International Union of Railways \(UIC\), 2023](#)).

With the expansion of the HSR network, the environmental impacts of HSR have attracted increasing scholarly attention. While many people think that investing in new HSR systems will automatically benefit the environment since HSR produces lower carbon dioxide (CO<sub>2</sub>) emissions per passenger kilometer than other transportation modes, a brief overview of the relevant literature reveals that the environmental impact of HSR is a complicated issue involving multiple factors and their complex interactions. Firstly, the extent to which new HSR lines attract passengers from other transport modes is conditioned by many factors, such as travel time/distance, frequencies of HSR, or structure of the aviation market ([Rajendran and Popfinger, 2022](#); [Yuan et al., 2023](#); [Gu and Wan, 2022](#)). Secondly, introducing HSR might not always have a net positive environmental effect in total as the expansion of an HSR network might create additional travel demand, as highlighted by [Givoni and Dobruszkes \(2013\)](#) and [D'alfonso et al. \(2015\)](#). [Chen et al. \(2016\)](#) indicate that HSR operations result in a net negative environmental impact because the mitigation of CO<sub>2</sub> emissions by modal shift could not offset the extra emissions from the induced travel. Thirdly, besides the environmental impacts directly arising from HSR operations, the new HSR investments might change the socioeconomic structure on its route, such as the structure of industry and population, by improving accessibility of the regions. Such transformations might have indirect effects on the environment, either negative or positive ([Nie and Zhang, 2023](#); [Yan et al., 2024](#); [Liu et al., 2023](#)). Finally, research examining the environmental impact of HSR projects from a life cycle perspective indicates that the construction of these projects carries significant environmental burdens. They note that the extent to which the environmental benefits from HSR operations offset the environmental burdens from HSR's construction and maintenance depends on several

factors, including the ridership and modal share of HSR and the characteristics of the HSR network (Kortazar et al., 2023; De Bortoli and Féraille, 2024).

While the existing literature examines the environmental impact of HSR by focusing on various individual aspects, as summarized above, there is currently no comprehensive review that integrates all of these aspects. Such a review is essential to address the complexity of the issue and provide guidance for future research and transport policy-making. To the best of our knowledge, two recent review articles touch upon the environmental impact of HSR. Jiang et al. (2021) review articles on the impacts of HSR projects on CO<sub>2</sub> emissions due to modal interactions. However, this study focuses specifically on CO<sub>2</sub> emissions and only includes studies considering modal interactions between HSR and the other transport modes. The study by Momenitabar et al. (2021) examines the socioeconomic effects of HSR in general and gives an overview by classifying articles according to main features such as frequency, overall tone, and impact areas. Unlike these studies, we aim to conduct a comprehensive literature review to investigate the environmental impacts of HSR by exploring the factors that affect the direction (e.g., negative, positive) and magnitude of these impacts, as well as the mechanisms by which HSR influences the environment. Finally, we propose a comprehensive framework incorporating all relevant aspects of HSR's environmental impacts. By doing this, we contribute to a broader understanding of the relationship between HSR and the environment and establish a solid foundation for future research in this area and for evaluating HSR projects from an environmental perspective.

The chapter is organized as follows. Section 2 explains the selection of literature and the review process. Section 3 explores the literature according to its focus and comprehensiveness, the factors influencing the environmental impact of HSR, and the mechanisms through which HSR affects the environment. Section 4 discusses the main findings and presents a general framework depicting the relationship between HSR and the environment.



## 2. The selection of articles and review process

Our review included only peer-reviewed journal articles. We selected journal articles from the Scopus database using a broad search string. Our search string includes articles whose titles contain the words “high” and “speed” together and whose contents of their abstracts, titles, or

keywords meet the following condition: (High AND speed AND rail AND environmental) OR (High AND speed AND rail AND pollution) OR (High AND speed AND rail AND environment) OR (High AND speed AND rail AND emissions). This search revealed 522 documents in total. Among them, we focused exclusively on articles investigating the environmental impacts of HSR. Specifically, we selected articles that compared the environmental performance of HSR with other modes of transportation, evaluated HSR's impact from a life cycle perspective, or assessed environmental quality before and after HSR began operations. We excluded articles discussing technical features to improve HSR's environmental performance from an engineering standpoint. Furthermore, we focused only on articles related to the impact of HSR on the physical environment, such as air quality or global warming, and excluded those focusing on noise pollution, which can adversely affect human health. To narrow our selection, we reviewed the abstracts of all 522 articles and eliminated those that fell outside the scope of our analysis. Ultimately, we chose 94 articles for a detailed examination. In analyzing the articles, we primarily read the abstracts and conclusions to determine the extent to which HSR affects the environment, the factors that influence its impact, and the impact mechanisms. We also examined other sections of the articles to uncover methodological issues, including data structure and analysis, as well as aspects that are not clearly explained but emphasized in the abstract or conclusions.



### **3. The impact of HSR on the environment**

Our review process identifies two categories of articles based on their focus and comprehensiveness: articles that examine (1) the environmental impacts of HSR operations and (2) the environmental impacts of HSR throughout its lifetime, including the construction phase. They include 78 and 16 articles, respectively (see [Table 1](#)). The first group of articles typically examines the environmental effects of an existing or proposed HSR network. They discuss the factors that influence the impact of HSR operations on the environment and the mechanisms through which this impact occurs. Most studies in the first group use a quasi-natural experimental analysis employing longitudinal environmental data (mainly measurements of various types of emissions over time) from a specific area before and after the introduction of HSR. Some studies utilize descriptive

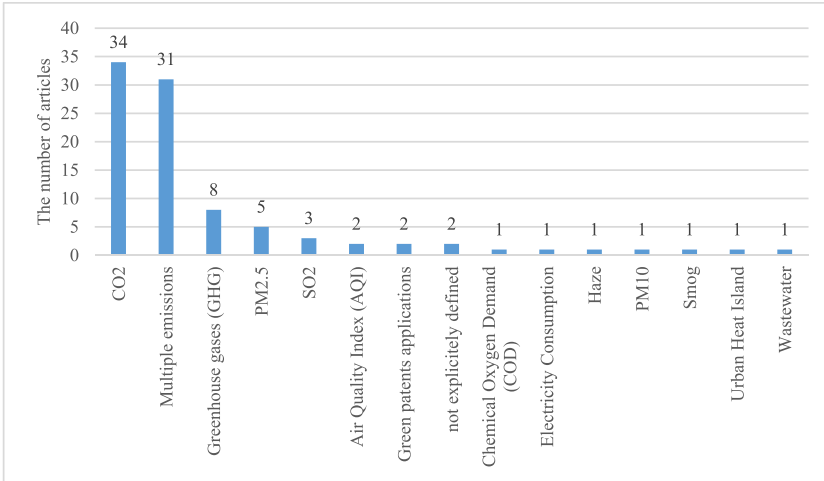
**Table 1** The number of articles according to the origin country of their empirical cases.

<b>The country of empirical HSR cases</b>	<b>The lifetime environmental impact of HSR</b>	<b>The environmental impact of HSR operations</b>	<b>Total</b>
<b>China</b>	3	64	<b>67</b>
<b>Europe</b>	6	9	<b>15</b>
<b>Australia</b>	2	1	<b>3</b>
<b>The USA</b>	5	1	<b>6</b>
<b>None</b>	0	1	<b>3</b>
<b>Total</b>	<b>16</b>	<b>78</b>	<b>94</b>

data analyses, simulations, and multiple criteria decision analysis (MCDA) methods.

The second group investigates the lifetime environmental impact of HSR. Their analysis includes emissions directly emitted during HSR operations and those generated during the construction and manufacturing phases of an HSR line or project. Thus, they predict HSR's lifetime impact on the environment and assess the change of environmental impact throughout the entire life cycle of an HSR line or project for about 50–60 years. These studies suggest that the construction phase of HSR projects puts a significant strain on the environment due to the extraction and use of large amounts of materials and energy resources. Ideally, the environmental benefits from HSR operations over time should outweigh these burdens, resulting in a net positive environmental impact (Kortazar et al., 2023; De Bortoli and Féraille, 2024). Studies in this group predict the payback time for the total emissions emitted during the operation and construction phases of an HSR project and also discuss factors influencing the duration of payback time. Estimations are usually based on a few hypothetical scenarios, depending on parameters such as vehicle technology and the modal shares of HSR and other modes. All studies in the second group adopt the life cycle assessment methodology except the two that use simulation models.

Table 1 presents the distribution of articles according to the origin country of the empirical cases they use. The table shows that of the 94 articles in our sample, the majority, 67 articles, analyze HSR lines or projects from China, 15 articles analyze HSR cases from Europe (or a



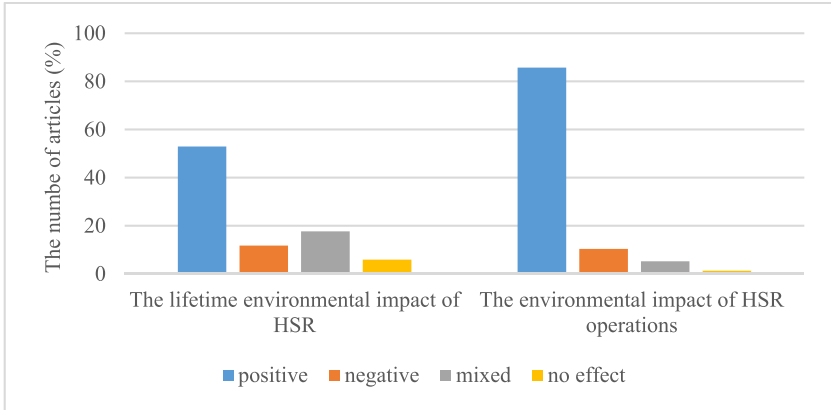
**Fig. 1 The number of articles according to environmental indicators.**

country from Europe), and the rest use cases from the USA and Australia. Finally, three of them do not use any specific cases. The fact that China's high-speed rail network attracted the most scholarly attention might be explained by the massive expansion of China's high-speed network relative to the rest of the world. [International Union of Railways \(UIR\) \(2023\)](#) reports that the length of the Chinese HSR network has reached 40,500 km during the last decade, contrary to 59,500 km worldwide.

[Fig. 1](#) depicts the environmental indicators<sup>1</sup> used in studies to assess the environmental impact of HSR. It shows that in the literature, emissions to the air are overwhelmingly the main topic. Out of 94 studies, almost half evaluate the environmental impact of HSR based on CO<sub>2</sub> or greenhouse gas (GHG) emissions. Around one-third of the studies use multiple indicators for comparison, such as CO<sub>2</sub>, SO<sub>2</sub>, or PM<sub>2.5</sub>. Other environmental indicators (such as wastewater) are hardly addressed.

[Fig. 2](#) shows the distribution of studies based on their overall evaluations of the impact of HSR on the environment. The figure reveals that approximately 50% of the studies assessing the lifetime environmental impact and 15% of those focusing on the environmental effects of HSR

<sup>1</sup> Some studies use specific composite indexes, which simultaneously contain environmental indicators such as CO<sub>2</sub>, SO<sub>2</sub>, or wastewater and other socioeconomic measures such as GDP, employment, and population. As we are mainly interested in the environmental impact of HSR, we excluded results related to indicators other than environmental ones in composite indexes.



**Fig. 2 The distribution of articles according to their overall assessment.**

operations conclude that the overall environmental impact of HSR is not positive. Furthermore, most studies emphasize that the environmental effects vary based on several factors, such as the type of emissions and industrial structure, even when they conclude that the overall environmental impact of HSR is positive. This is noteworthy since HSR typically generates lower emissions per passenger kilometer than other transport modes, and policymakers often consider HSR an environmentally friendly mode of transportation (see [Section 1](#)). The figure indicates that studies examining the lifetime environmental impact of HSR are generally less favorable than those focusing on HSR operations. This difference can be attributed to the fact that the non-operational phases of HSR, such as construction, manufacturing, and maintenance, have more negative environmental impacts than the operational phase of HSR.

The following sub-sections, [Sections 3.1](#) and [3.2](#), explore the environmental impacts of HSR operations and the lifetime impact of HSR on the environment, respectively.

### 3.1 The environmental impacts of HSR operations

Research on the environmental impacts of HSR operations primarily examines how HSR's environmental impact varies across different factors and explains the mechanisms contributing to this variation. In [Section 3.1.1](#), we will first introduce the key mechanisms through which HSR operations affect the environment. Following this, based on the literature, we will discuss the factors that influence HSR's environmental impact and the underlying mechanisms.

### 3.1.1 Environmental impact mechanisms of HSR operations

Our literature review identifies two mechanisms of impact: (1) direct impact mechanisms and (2) indirect impact mechanisms. The direct impact mechanisms relate to HSR operations and arise from two key effects: substitution and traffic generation. The net environmental impact of HSR results from a trade-off between these two processes. In other words, the net effect depends on how many passengers shift from other modes of transportation to HSR (the substitution effect) and the extent to which HSR generates new travel demand (the traffic generation effect). Generally, a higher rate of substitution enhances the positive environmental impact of HSR, while an increase in induced travel demand leads to a negative environmental impact. In contrast, the indirect impact of HSR pertains to how its operations affect the socioeconomic structures of regions and cities. In other words, a specific HSR network or line can change the socioeconomic structure of these areas, which in turn influences the environment.

Table 2 presents studies investigating the direct impact of HSR on the environment. Among these studies, all except two focus on the substitution

**Table 2** Substitution and traffic generation effect of HSR.

Article	Environmental indicators	Overall impact	Substitution	Traffic generation
Yuan et al. (2023)	CO <sub>2</sub>	Positive	Yes	
Yao et al. (2023)	CO <sub>2</sub>	Positive	Yes	
Meng et al. (2023)	PM <sub>2.5</sub>	Positive	Yes	
Avogadro et al. (2021)	CO <sub>2</sub>	Positive	Yes	
Boehm et al. (2021)	CO <sub>2</sub>	Positive	Yes	
Liu et al. (2022a)	CO <sub>2</sub>	Positive	Yes	
Jia et al. (2021)	CO <sub>2</sub>	Positive	Yes	
Lin et al. (2021)	GHG	Positive	Yes	
Liu et al. (2022b)	AQI	Positive	Yes	
Rajendran and Popfinger (2022)	CO <sub>2</sub>	Positive	Yes	

Strauss et al. (2021)	CO <sub>2</sub>	Positive	Yes	
Zhao et al. (2021)	AQI, PM <sub>2.5</sub> , PM <sub>10</sub> , and O <sub>3</sub>	Positive	Yes	
Guo et al. (2020)	CO, PM <sub>2.5</sub> , and O <sub>3</sub>	Positive	Yes	
Wang et al. (2019)	CO <sub>2</sub>	Positive	Yes	
Prussi and Lonza (2018)	GHG	Positive	Yes	
Dalkic et al. (2017)	CO <sub>2</sub>	Positive	Yes	
Krishnan et al. (2015)	CO <sub>2</sub>	Positive	Yes	
Robertson (2013)	CO <sub>2</sub>	Positive	Yes	
Álvarez (2010)	CO <sub>2</sub>	Positive	Yes	
Tang et al. (2023)	CO <sub>2</sub>	Positive	Yes	Yes
Gu and Wan (2022)	CO <sub>2</sub>	Negative	Yes	Yes
Sun and Li (2021)	CO <sub>2</sub>	Positive	Yes	Yes
D'Alfonso et al. (2015)	Environmental Pollution	Mixed	Yes	Yes
Chen et al. (2016)	CO <sub>2</sub>	Negative		Yes
D'Alfonso et al. (2016)	HC, CO, NO <sub>x</sub> , SO <sub>2</sub> , PM, GHG	Mixed	Yes	Yes
Li et al. (2019)	CO <sub>2</sub>	Negative		Yes

effect associated with HSR. Research on the substitution effect indicates that HSR generally has a positive environmental impact. This positive effect is mainly attributed to a shift from more polluting transportation modes, such as air and road transportation, to HSR once it begins operating. In contrast, only a few studies examine the traffic generation effect of HSR. These studies suggest that HSR can negatively impact the environment because it induces additional travel demand. This induced travel can lead to increased economic activity, higher energy consumption, and

urbanization, all of which place additional strain on the environment. Some studies address both effects, concurrently discussing the trade-off between substitution and traffic generation.

Table 3 contains studies discussing the indirect impacts of HSR on the environment. These impacts include the transformation of the industrial structure and economic agglomerations along the rail route, as well as an increase in environmental awareness, which generates social and political pressure for stronger environmental regulations. Almost all these studies agree that the opening of HSR results in significant time-space convergence by improving accessibility between areas connected by HSR. This convergence between cities facilitates the flow of resources and the diffusion of knowledge and technology. These circumstances facilitate environmental improvement via two major changes in industrial structure in these areas. Firstly, it enhances the production efficiency of enterprises and accelerates the utilization of green technologies. Secondly, such an environment encourages the development of service and knowledge-based industries that are typically less polluting. Furthermore, the dissemination of information about polluting industrial activities raises environmental awareness, which increases political and social pressure on governments to strengthen environmental regulations and on enterprises to green their activities. Consequently, studies suggest that these changes in the structure of industrial agglomerations and the social environment enable the reduction of industrial emissions over time. In contrast, some studies suggest that changes in industrial structure and economic agglomeration triggered by the opening of HSR have a negative impact on the environment. They mainly state that the introduction of HSR leads to higher emissions by increasing accessibility and intensifying economic agglomeration, industrial energy consumption, and land development. Furthermore, some studies suggest that while industrial pollutants decrease in regions connected with HSR due to the industrial transformation, more polluting industries migrate to other regions, thereby shifting pollution to different places.

### ***3.1.2 Variations in the environmental impacts of HSR operations and underlying mechanisms***

Our analysis reveals that the impact of HSR on the environment varies depending on four groups of factors: (1) the type of environmental indicators, (2) time, (3) economic and industrial characteristics of areas, (4) locational and physical characteristics of areas, and (5) features of the transport system.

**Table 3 Indirect impact mechanisms of HSR.**

Article	Environmental indicators	Overall impact	Change in industrial structure/economic agglomeration	Social/political pressure for environmental regulations
Yan et al. (2024)	NDVI, SO <sub>2</sub> , and dust	Negative	Yes	
Nie and Zhang (2023)	CO <sub>2</sub>	Positive	Yes	
Wang et al. (2023b)	COD	Positive	Yes	
Wang et al. (2023a)	Wastewater, SO <sub>2</sub> , and smoke	Positive	Yes	
Zhou et al. (2023)	not explicitly defined	Positive	Yes	
Feng et al. (2024)	Coal and fuel oil consumption	Positive	Yes	
Gao and Wang (2023)	Wastewater, SO <sub>2</sub> , soot, and CO <sub>2</sub>	Positive	Yes	
Yan et al. (2023)	SO <sub>2</sub>	Positive	Yes	
Yang et al. (2023)	CO <sub>2</sub> , NOX, CO, SO <sub>2</sub> and PM <sub>2.5</sub>	Mixed	Yes	
Su and Xie (2023)	PM <sub>2.5</sub>	Positive	Yes	
Meng et al. (2023)	PM <sub>2.5</sub>	Positive	Yes	
Chen et al. (2024)	Wastewater, SO <sub>2</sub> , and PM	Positive	Yes	

*(continued)*

**Table 3 Indirect impact mechanisms of HSR. (cont'd)**

Article	Environmental indicators	Overall impact	Change in industrial structure/economic agglomeration	Social/political pressure for environmental regulations
Liu et al. (2024)	PM <sub>2.5</sub> and CO <sub>2</sub>	Positive	Yes	
Chang et al. (2021)	PM <sub>2.5</sub>	Positive	Yes	
Wang et al. (2022)	Wastewater, SO <sub>2</sub> , and smoke	Positive	Yes	
Jiang and Liu (2022)	Soot, CO <sub>2</sub> , wastewater, power consumption, PM <sub>2.5</sub> , industrial solids, and the sewage treatment	Positive	Yes	
Lin and Jia (2022)	CO <sub>2</sub>	Positive	Yes	
Li and Guo (2021)	COD, NH <sub>3</sub> N, SO <sub>2</sub> , NO <sub>x</sub>	Negative	Yes	
Zhou and Zhang (2022)	SO <sub>2</sub>	Positive	Yes	
Liu et al. (2022a)	CO <sub>2</sub>	Positive	Yes	
Liu et al. (2023)	COD, SO <sub>2</sub> , dust, and wastewater	Positive	Yes	
Jia et al. (2021)	CO <sub>2</sub>	Positive	Yes	
Li et al. (2022)	Wastewater, SO <sub>2</sub> , and dust	Positive	Yes	
Fang (2021)	Smog	Positive	Yes	

Chen et al. (2022a)	CO <sub>2</sub>	Positive	Yes
Zhu et al. (2022)	CO <sub>2</sub>	Positive	Yes
Liu et al. (2022b)	AQI	Positive	Yes
Sun and Li (2021)	CO <sub>2</sub>	Positive	Yes
Zhao et al. (2021)	AQI, PM <sub>2.5</sub> , PM <sub>10</sub> , and O <sub>3</sub>	Positive	Yes
Guo et al. (2021)	Wastewater	Positive	Yes
Li et al. (2019)	CO <sub>2</sub>	Negative	Yes
Zhang et al. (2021)	PM <sub>2.5</sub>	Positive	Yes
Jiao and Fang (2018)	Urban Heat Island	Negative	Yes
Yang et al. (2019)	SO <sub>2</sub>	Positive	Yes
Yu and Wan (2022)	Green patent applications	Positive	Yes
Li and Cheng (2022)	CO <sub>2</sub>	Positive	Yes
Han and Wang (2023)	Green patent applications	Positive	Yes
Chen et al. (2020)	PM <sub>10</sub>	Positive	Yes
Chen et al. (2023b)	CO <sub>2</sub>	Positive	Yes

### 3.1.2.1 The type of environmental indicators

The articles presented in [Table 4](#) demonstrate that the environmental impact of HSR varies depending on the types of emissions. This variation primarily arises from two factors: (1) differences in emission sources, which may include various sectors such as transportation and heavy industry, and (2) how the implementation of HSR affects these emission sources through direct and indirect mechanisms. For example, [Yang et al. \(2023\)](#) emphasize that CO<sub>2</sub>, CO, and NO<sub>x</sub> emissions may rise in certain regions as output and energy consumption in the heavy industry sector increase following the start of HSR operations. Conversely, emissions decline in other areas due to reduced energy consumption within the transport sector, as a result of the substitution effect associated with HSR. Furthermore, while HSR decreases energy use in road transport, PM<sub>2.5</sub> and SO<sub>2</sub> emissions may still increase in some regions. This is because the transport sector contributes only a minor proportion of these pollutants, and HSR can stimulate the growth of industries that are significant sources of these emissions. In a similar vein, [Guo et al. \(2020\)](#) find that HSR negatively impacts CO emissions by decreasing road traffic; however, it does not have a significant effect on PM<sub>2.5</sub> and O<sub>3</sub> emissions, as their primary sources originate outside the transport sector. [Liu et al. \(2024\)](#) explain that in large cities, HSR can lead to higher PM<sub>2.5</sub> emissions due to the increased movement of labor and resources. Nevertheless, HSR contributes to reducing CO<sub>2</sub>

**Table 4 Environmental impact of HSR across the type of environmental indicators.**

Articles	Overall impact	Environmental indicators
<a href="#">Yang et al. (2023)</a>	Mixed	CO, CO <sub>2</sub> , NO <sub>x</sub> , SO <sub>2</sub> , PM <sub>2.5</sub>
<a href="#">Liu et al. (2024)</a>	Positive	PM <sub>2.5</sub> , CO <sub>2</sub>
<a href="#">Guo et al. (2020)</a>	Positive	CO, PM <sub>2.5</sub> , O <sub>3</sub>
<a href="#">Gao et al. (2022)</a>	No effect	SO <sub>2</sub> , COD
<a href="#">Chen et al. (2024)</a>	Positive	SO <sub>2</sub> , PM
<a href="#">D'Alfonso et al. (2016)</a>	Mixed	GHG, HC, CO, NO <sub>x</sub> , SO <sub>2</sub> and PM
<a href="#">Zhao et al. (2021)</a>	Positive	PM <sub>2.5</sub> , PM <sub>10</sub> , O <sub>3</sub>

emissions in these large cities, as production activities tend to shift to smaller cities that provide better locational conditions, facilitated by the enhanced accessibility that HSR offers.

### 3.1.2.2 Time

The articles in [Table 5](#) suggest that the environmental impact of HSR emerges gradually over time and becomes noticeable a few years after HSR operations begin. This is primarily due to two reasons. Firstly, HSR has a more significant environmental impact over time as the network expands or its capacity increases. For example, [Tang et al. \(2023\)](#) and [Li et al. \(2022\)](#) indicate that the impact of HSR on environmental pollution increases over time alongside the development of the HSR system. Secondly, the environmental effects of HSR gradually become evident as socioeconomic changes triggered by its operations unfold slowly. The most noticeable effect on CO<sub>2</sub> emissions is typically observed with a lag of three periods following the beginning of HSR operations, because the construction of

**Table 5 Change in the environmental impact of HSR over time.**

Article	Overall impact	Environmental indicators
<a href="#">Yan and Park (2023)</a>	Positive	CO <sub>2</sub>
<a href="#">Sun and Li (2021)</a>	Positive	CO <sub>2</sub>
<a href="#">Zhu et al. (2022)</a>	Positive	CO <sub>2</sub>
<a href="#">Tang et al. (2023)</a>	Positive	CO <sub>2</sub>
<a href="#">Lin and Jia (2022)</a>	Positive	CO <sub>2</sub>
<a href="#">Li et al. (2022)</a>	Positive	Wastewater, SO <sub>2</sub> , smoke
<a href="#">Wong et al. (2022)</a>	Positive	Wastewater, SO <sub>2</sub> , smoke
<a href="#">Wang et al. (2023a)</a>	Positive	Wastewater, SO <sub>2</sub> , smoke
<a href="#">Liu et al. (2022b)</a>	Positive	AQI
<a href="#">Wang et al. (2022)</a>	Positive	Wastewater, SO <sub>2</sub> , smoke
<a href="#">Zhao et al. (2020)</a>	Positive	AQI
<a href="#">Guo et al. (2020)</a>	Positive	CO, PM <sub>2.5</sub> , O <sub>3</sub>

HSR primarily facilitates the free flow of resources, which takes time to manifest, according to findings of [Zhu et al. \(2022\)](#). Similarly, [Liu et al. \(2022b\)](#) highlight that once HSR begins operations, its impact continues to evolve over time, as it takes a while for both direct and indirect effects to be realized. Additionally, the impact of HSR on emissions may vary throughout the day or week, influenced by the chemical characteristics of air quality emissions. [Guo et al. \(2020\)](#) find that reductions in emissions (CO, PM<sub>2.5</sub>, O<sub>3</sub>) occur during weekdays and HSR operation hours. This is likely due to the fact that air quality emissions, such as CO and PM, have short atmospheric lifetimes, and their concentrations can fluctuate at different times of the day, week, or season ([Bodor et al., 2020](#); [IPCC, 2007](#)).

### 3.1.2.3 Economic and industrial characteristics of areas

The literature examines how HSR's environmental impact varies based on the economic and industrial characteristics of the areas connected by HSR under the following sub-categories:

- The level of economic development
- The type of industrial structure
- Innovation level
- The level of environmental regulations/investments

[Table 6](#) illustrates that the level of economic development in HSR cities may either enhance or diminish the effect of HSR on the environment. Most studies conclude that this impact is likely to be more pronounced in areas with advanced development. [Nie and Zhang \(2023\)](#), [Gao and Wang \(2023\)](#), and [Yang et al. \(2019\)](#) assert that HSR exerts a more positive influence on the environment of economically developed areas, as these regions are more adept at attracting high-skilled workers and quality international investment for technological advancements and improved resource allocation, thereby facilitating local green transitions and reducing environmental pollution. [Liu, Zhang et al. \(2023\)](#) argue that the positive environmental effect of HSR is more evident in these areas due to an increased desire for a better urban environment, compelling enterprises to adhere to stricter pollution emission standards. Moreover, developed cities tend to invest more resources in urban environmental governance, thereby enhancing the emission reduction capacity of businesses. [Liu et al. \(2022b\)](#) note that HSR positively impacts the environment in economically developed areas due to a higher volume of traffic, which strengthens the HSR transport substitution effect in these regions. Conversely, [Li et al. \(2019\)](#) and [Yan et al. \(2024\)](#) contend that HSR

**Table 6 The environmental impact of HSR according to the economic development level<sup>a</sup>.**

Article	Environmental indicators	Overall impact	Impact on economically developed areas	Impact on economically less developed areas
Yan et al. (2024)	NDVI, SO <sub>2</sub> , and dust	Negative	More negative	
Nie and Zhang (2023)	CO <sub>2</sub>	Positive	More positive	
Gao and Wang (2023)	Wastewater, SO <sub>2</sub> , soot, and CO <sub>2</sub>	Positive	More positive	
Yan et al. (2023)	SO <sub>2</sub>	Positive		More positive
Tang et al. (2023)	CO <sub>2</sub>	Positive	More positive	
Liu et al. (2023)	COD, SO <sub>2</sub> , dust, and wastewater	Positive	More positive	
Liu et al. (2022b)	AQI	Positive	Positive	
Zhao et al. (2021)	AQI, PM <sub>2.5</sub> , PM <sub>10</sub> , and O <sub>3</sub>	Positive	More positive	
Sun et al. (2020)	Wastewater, SO <sub>2</sub>	Positive		More positive
Li et al. (2019)	CO <sub>2</sub>	Negative	More negative	
Zhang et al. (2021)	PM <sub>2.5</sub>	Positive		More positive
Yang et al. (2019)	SO <sub>2</sub>	Positive	More positive	

<sup>a</sup>The “Overall Impact” column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact varies according to economic development level, the “Impact on Economically (Less) Developed Areas” columns specify how these differences manifest.

operations contribute to environmental pollution in these developed areas by encouraging travel and economic activities. The adverse pollution effects outweigh the benefits of environmental improvements.

On the other hand, some researchers observe a more significant impact in less developed areas. [Yan et al. \(2023\)](#) suggest that HSR services lessen reliance on energy extraction and mitigate the degradation of natural resources in less developed regions by fostering more diverse industrial development opportunities through the flow of production factors and technology. Furthermore, [Sun et al. \(2020\)](#) argue that less developed areas can better integrate with developed regions due to the reduced travel time and distance provided by HSR connections, thereby enhancing their environmental efficiency.

Studies in [Table 7](#) indicate that the environmental effects of HSR on specific cities vary based on whether the industries are primarily resource/non-resource-based, technology/labor-intensive, or secondary, as well as whether the cities exhibit high or low levels of marketization.

Most studies focusing on (non-)resource-based cities indicate that HSR operations improve environmental conditions in resource-based cities that primarily rely on extracting and processing natural resources, such as minerals and oil. This improvement is primarily driven by industrial transformation. HSR facilitates the exchange of information, fosters technological innovation, and enhances the flow of resources, which helps reduce dependence on energy-intensive and heavily polluting industries ([Wang et al., 2022](#), [Jia et al., 2021](#), [Jiang and Liu, 2022](#), [Xu et al., 2022](#)). Additionally, HSR improves resource allocation, production processes, and energy efficiency within these heavily polluting industries and thus decreases industrial emissions in these regions ([Liu et al., 2024](#); [Gao et al., 2022](#)). However, the findings regarding the environmental effects of HSR in non-resource-based cities are less conclusive. While studies by [Tang et al. \(2023\)](#), [Lin and Jia \(2022\)](#), and [Wang et al. \(2022\)](#) suggest that HSR has no significant environmental impact in these cities, other research by [Li and Cheng \(2022\)](#) and [Yu and Wan \(2022\)](#) reports a positive environmental effect of HSR. Their findings imply that non-resource-based cities may experience substantial additional environmental benefits from HSR, as they already exhibit higher levels of technological innovation and environmental awareness.

Some studies indicate a significant reduction in carbon emissions in cities with a strong presence of secondary industries, primarily involved in manufacturing, after HSR operations begin. [Chen et al. \(2023b\)](#) argue that

**Table 7 The environmental impact of HSR according to the industrial structure<sup>a</sup>.**

Article	Environmental indicators	Overall impact	Impact on areas with a particular industrial structure
<b>Resource or Non-Resource-based Industries</b>			
Feng et al. (2024)	Coal and fuel oil consumption	Positive	More positive in resource-based cities, capital, and technology-intensive and high-carbon industries
Gao et al. (2022)	COD and SO <sub>2</sub>	No effect	Positive for cities with heavily polluting industries
Tang et al. (2023)	CO <sub>2</sub>	Positive	Positive in resource-based cities; no effect in non-resource-based cities
Lin and Jia (2022)	CO <sub>2</sub>	Positive	Positive in resource-based cities; no effect in non-resource-based cities
Liu et al. (2024)	PM <sub>2.5</sub> and CO <sub>2</sub>	Positive	More positive in resource-based cities
Jiang and Liu (2022)	Soot, CO <sub>2</sub> , wastewater, power consumption, PM <sub>2.5</sub> , industrial solids, and the sewage treatment	Positive	Positive in resource-based cities
Xu et al. (2022)	SO <sub>2</sub> and power consumption	Positive	Positive in resource-based cities
Jia et al. (2021)	CO <sub>2</sub>	Positive	More positive in resource-based cities
Wang et al. (2022)	Wastewater, SO <sub>2</sub> , smoke	Positive	Positive in resource-based cities; no effect in non-resource-based cities
Li and Cheng (2022)	CO <sub>2</sub>	Positive	More positive in non-resource-based cities
Yu and Wan (2022)	Green patent applications	Positive	Positive in non-resource-based cities

*(continued)*

**Table 7 The environmental impact of HSR according to the industrial structure<sup>a</sup>.**  
(cont'd)**Secondary Industries**

Chen et al. (2022a)	CO <sub>2</sub>	Positive	More positive in cities with secondary industry
Chen et al. (2023b)	CO <sub>2</sub>	Positive	More positive in cities with external factors and secondary industries

**High or Low Marketization**

Chen et al. (2020)	PM <sub>10</sub>	Positive	More positive in cities with lower marketization; less positive in cities with higher marketization
Su and Xie (2023)	PM <sub>2.5</sub>	Positive	Positive in cities with low marketization; no effect in cities with high marketization

**Technology or Labor-Intensive Industries**

Wang et al. (2023b)	COD	Positive	More positive in cities with technology and labor-intensive industries
Wang et al. (2023a)	Wastewater, SO <sub>2</sub> , smoke	Positive	Positive in cities with advanced industry
Liu et al. (2023)	COD, SO <sub>2</sub> , dust, and wastewater	Positive	Positive in cities with technology-intensive industries, negative in cities with labor-intensive industry

**Others**

Yan et al. (2024)	NDVI, SO <sub>2</sub> , and dust	Negative	Positive in ecotourism cities
Zhou and Zhang (2022)	SO <sub>2</sub>	Positive	More positive in cities with dirty, state-owned, foreign, and large firms

<sup>a</sup>The “Overall Impact” column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact varies according to the industrial structure, the “Impact on Areas with a Particular Industrial Structure” column specifies how these differences manifest.

the secondary sector depends on external factors. Therefore, external social pressure motivates these cities to enhance their emissions reduction efforts in this sector. Additionally, [Chen et al. \(2022a\)](#) point out that the positive impact of HSR on reducing carbon emissions is particularly noticeable in areas where the proportion of secondary industries is higher. A more significant impact is observed due to the industrial upgrades in the secondary sector facilitated by HSR operations.

The literature presented in [Table 7](#) indicates that HSR operations reduce environmental pollution to a larger extent in areas with lower levels of marketization. According to [Chen et al. \(2020\)](#), this effect may stem from HSR's ability to enhance the flow of people and information in these less-developed markets. This increased connectivity exerts institutional pressure on both industries and local governments to address environmental issues. Furthermore, HSR accelerates the movement of economic resources and technology ([Su and Xie, 2023](#)), which likely leads to improved production processes and energy efficiency, thereby reducing industrial emissions in these regions.

Studies consistently show that the introduction of HSR reduces polluting emissions from technology-intensive industries. HSR enhances the flow of high-quality production factors and encourages research and development (R&D) investments, contributing to a decrease in pollution emissions generated by these industries ([Liu et al., 2023](#), [Wang et al., 2023b](#)). Based on similar reasoning, [Liu et al. \(2023\)](#) argue that HSR operations, which promote technological advancement, do not affect pollution emissions from labor-intensive industries since such industries typically do not use high technology. Conversely, [Wang et al. \(2023b\)](#) contend that HSR also helps lowering emissions in labor-intensive sectors. This occurs through savings on labor mobility costs, optimized resource allocation, and enhanced knowledge flow.

Finally, studies examining the environmental impacts of HSR on different types of firms indicate that HSR has a more significant effect on the environmental efficiency of foreign and state-owned enterprises compared to domestic private companies. Foreign firms are more committed to cleaner production practices, and state-owned enterprises have greater incentives to enhance their environmental efficiency because of China's environmental policies than domestic ones ([Zhou and Zhang, 2022](#)). Additionally, the researchers argue that HSR tends to enhance the environmental efficiency of firms with higher levels of pollution more than others. This is because these firms have a greater potential for

improvement in their environmental practices. [Yan et al. \(2024\)](#) analyze the environmental impact of HSR operations in ecotourism-oriented cities. These cities are motivated to maintain and enhance their environmental quality following the launch of HSR services, as HSR amplifies the environmental quality of these cities and makes them more attractive to tourists.

Most studies examining the impact of HSR on regions with high levels of technological innovation, as illustrated in [Table 8](#), indicate that HSR operations positively affect the environment in technologically advanced areas. These studies suggest that the start of HSR services facilitates the exchange of advanced knowledge and highly skilled workers between regions. Companies located in areas with advanced technological structures are more likely to benefit from these exchanges and contribute to reducing emissions in these areas. Conversely, [Chen et al. \(2020\)](#) find that HSR has a limited impact in areas with advanced technology. In regions with a lower level of technological advancement, HSR increases social and institutional pressure on companies to improve their environmental efficiency by promoting the flow of information from other regions. However, in areas with low information asymmetries, due to their advanced technology, the contribution of HSR operations to the information environment and, consequently, the improvement of environmental quality is limited.

**Table 8 The environmental impact of HSR according to the innovation level<sup>a</sup>.**

Article	Environmental indicators	Overall impact	Impact on areas with high levels of innovation
<a href="#">Nie and Zhang (2023)</a>	CO <sub>2</sub>	Positive	More positive
<a href="#">Feng et al. (2024)</a>	Coal and fuel oil consumption	Positive	More positive
<a href="#">Yan and Park (2023)</a>	CO <sub>2</sub>	Positive	More positive
<a href="#">Chen et al. (2020)</a>	PM <sub>10</sub>	Positive	Less positive

<sup>a</sup>The "Overall Impact" column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact differs in areas with high levels of innovation, the "Impact on Areas with High Levels of Innovation" column specifies how these differences manifest.

#### 3.1.2.4 Locational and physical characteristics of areas

Some literature examines how the environmental impact of HSR varies based on the locational and physical characteristics of areas connected by HSR, considering city size and neighboring regions of the HSR network.

Table 9 highlights two contrasting conclusions regarding the environmental effects of HSR based on city size. On the one hand, some studies indicate that HSR development has a more positive environmental impact on large cities than on small ones. In fact, this research suggests that HSR operations may have no effect, or even negative effects, in small cities (see, for example, studies by Nie and Zhang (2023), Liu et al. (2023), and Lin and Jia (2022)). This is due to the fact that large cities have advantages in attracting innovation, technology, and resources due to their well-developed physical and socioeconomic infrastructures. HSR further enhances these favorable conditions in these cities by improving accessibility. As a result, this can lead to reduced emissions through increased production efficiency, industrial upgrading and transformation, and the adoption of green technologies (Nie and Zhang, 2023; Zhou et al., 2023; Li and Cheng, 2022). However, Tang et al. (2023) note that an excessively large population may hinder HSR's carbon reduction benefits by diminishing its marginal effects.

On the other hand, some studies indicate that the emission reduction effect of HSR in large cities is limited, nonexistent, or even negative, while being positive in small cities. They suggest that large cities already possess high-quality production factors, high production efficiency, and technological advancement, and thus, HSR's contribution to green transformation in such areas is limited (Yan et al., 2023; Liu et al., 2022a). Additionally, Sun and Li (2021) report that the start of HSR operations increases environmental pollution in large cities as the traffic creation effect is greater than the traffic substitution effect in these areas. This is because the agglomeration of laborers in large cities, triggered by HSR operations, leads to the expansion of urban space and, consequently, increases the use of private cars and other non-green transportation modes. However, HSR improves environmental quality in small cities as the transportation substitution effect is greater than the transportation creation effect there. The reason is that small cities do not experience agglomerations and an increase in the use of private cars like large cities.

Finally, the findings of Liu et al. (2024) differ for PM<sub>2.5</sub> and CO<sub>2</sub> emissions. This research indicates that HSR impacts PM<sub>2.5</sub> and CO<sub>2</sub> emissions differently in small and large cities. This primarily stems from the fact that these two types of emissions originate from different sources. HSR operations increase PM<sub>2.5</sub> emissions in large cities due to increased urban

**Table 9 The environmental impact of HSR according to the city size<sup>a</sup>.**

Article	Environmental indicators	Overall impact	Impact on small/medium/large cities
Tang et al. (2023)	CO <sub>2</sub>	Positive	Positive/more positive in large cities; negative/no effect in small cities
Nie and Zhang (2023)	CO <sub>2</sub>	Positive	
Zhou et al. (2023)	not explicitly defined	Positive	
Liu et al. (2023)	COD, SO <sub>2</sub> , dust, and wastewater	Positive	
Jia et al. (2021)	CO <sub>2</sub>	Positive	
Gao et al. (2022)	COD and SO <sub>2</sub>	No effect	
Yang et al. (2019)	SO <sub>2</sub>	Positive	
Li and Cheng (2022)	CO <sub>2</sub>	Positive	
Meng et al. (2023)	PM <sub>2.5</sub>	Positive	
Lin and Jia (2022)	CO <sub>2</sub>	Positive	
Wang et al. (2023a)	Wastewater, SO <sub>2</sub> , smoke	Positive	
Li et al. (2019)	CO <sub>2</sub>	Negative	
Wang and Qiu (2023)	Wastewater, waste gas, dust	Positive	Positive/more positive in small cities; negative/no effect in large cities
Feng et al. (2024)	Coal and fuel oil consumption	Positive	
Yan et al. (2023)	SO <sub>2</sub>	Positive	
Liu et al. (2022a)	CO <sub>2</sub>	Positive	
Sun et al. (2020)	Wastewater, SO <sub>2</sub>	Positive	
Chen et al. (2022b)	CO <sub>2</sub>	Negative	
Su and Xie (2023)	PM <sub>2.5</sub>	Positive	
Sun and Li (2021)	CO <sub>2</sub>	Positive	

Zhang et al. (2021)	PM <sub>2.5</sub>	Positive	No difference between large and small cities
Liu et al. (2024)	PM <sub>2.5</sub> and CO <sub>2</sub>	Positive	For PM <sub>2.5</sub> positive in small/medium cities, negative in large cities; for CO <sub>2</sub> positive in large/medium cities, negative in small cities

<sup>a</sup>The “Overall Impact” column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact varies according to the city size, the “Impact on Small/Medium/Large Cities” column specifies how these differences manifest.

illnesses and environmental degradation caused by the agglomeration effect intensified by HSR while decreasing it in small cities. Conversely, the introduction of HSR reduces CO<sub>2</sub> emissions in large cities because of the agglomeration of production factors and advanced technology that fosters favorable conditions for industrial upgrading and green transformation. Additionally, the study by Zhang et al. (2021) find no difference between large and small cities regarding HSR’s environmental effects and argues that HSR reduces pollutant emissions in both small and large cities.

Table 10 illustrates that HSR operations affect not only the environment of cities along the HSR network but also that of surrounding areas. Most studies indicate that the environmental impact on neighboring areas of the HSR network varies based on the following characteristics of HSR cities and their adjacent areas.<sup>2</sup>

- The distance between HSR cities and neighboring areas
- Whether neighboring cities are with/without HSR
- The level of economic development,
- The type of industrial structure,
- The size of cities,
- Environmental/other transport policies

<sup>2</sup> Some studies do not reference specific characteristics of the HSR cities and their surroundings although they mention that HSR affects the environment of HSR cities and their surroundings differently (see the upper lines of Table 10).

**Table 10 The environmental impact of HSR on neighboring areas of the HSR network<sup>a</sup>.**

Features of HSR cities and their neighboring areas	Article	Environmental indicators	Overall impact	Impact on neighboring areas
<b>No Specification</b>	Liu et al. (2024)	PM <sub>2.5</sub> and CO <sub>2</sub>	Positive	Positive
	Chang et al. (2021)	PM <sub>2.5</sub>	Positive	Negative
	Zhou and Zhang (2022)	SO <sub>2</sub>	Positive	No effect
	Huang et al. (2023)	PM <sub>2.5</sub> , PM <sub>10</sub> , SO <sub>2</sub> , CO, NO <sub>2</sub> , and O <sub>3</sub>	Positive	Negative; no effect
	Meng et al. (2023)	PM <sub>2.5</sub>	Positive	Positive
	Wang et al. (2022)	Wastewater, SO <sub>2</sub> , and smoke	Positive	Positive
	Lin and Jia (2022)	CO <sub>2</sub>	Positive	Negative
	Liu et al. (2022a)	CO <sub>2</sub>	Positive	Positive
	Li et al. (2022)	Wastewater, SO <sub>2</sub> , and dust	Positive	Negative
	Zhu et al. (2022)	CO <sub>2</sub>	Positive	Positive; negative
<b>The distance between HSR cities and neighboring areas</b>	Nie and Zhang (2023)	CO <sub>2</sub>	Positive	More positive if neighboring cities are closer to the HSR city

Yu and Wan (2022)	Green patent applications	Positive	More positive if neighboring cities are closer to the HSR city
Guo et al. (2021)	Wastewater	Positive	More positive if neighboring cities are closer to the HSR city
Jia et al. (2021)	CO <sub>2</sub>	Positive	More positive if neighboring cities are closer to the HSR city
Liu et al. (2022b)	AQI	Positive	More positive if neighboring cities are closer to the HSR city
<b>Neighbors with/without HSR</b>			
Yan et al. (2023)	SO <sub>2</sub>	Positive	More positive if neighboring cities are without HSR
Tang et al. (2023)	CO <sub>2</sub>	Positive	More positive if neighboring cities are with HSR
<b>The level of Economic Development</b>			
Yan et al. (2024)	NDVI, SO <sub>2</sub> , and dust	Negative	Positive if HSR city is more developed; no effect if HSR city is less developed
Wei and Liu (2023)	CO <sub>2</sub> , SO <sub>2</sub> , PM <sub>2.5</sub> , NDVI, wastewater, cultivated/constructed land, inversion, water consumption	Positive	More positive if HSR city is more developed

(continued)

**Table 10 The environmental impact of HSR on neighboring areas of the HSR network<sup>a</sup>. (cont'd)**

Features of HSR cities and their neighboring areas	Article	Environmental indicators	Overall impact	Impact on neighboring areas
	Gao and Wang (2023)	Wastewater, SO <sub>2</sub> , soot, and CO <sub>2</sub>	Positive	Negative if HSR city is more developed; positive if HSR city is less developed;
	Yan et al. (2023)	SO <sub>2</sub>	Positive	More positive if HSR city is less developed
	Li and Guo (2021)	COD, NH <sub>3</sub> , SO <sub>2</sub> , and NO <sub>x</sub>	Negative	More negative if HSR city is more developed
<b>The type of Industrial Structure</b>	Wei and Liu (2023)	CO <sub>2</sub> , SO <sub>2</sub> , PM <sub>2.5</sub> , NDVI, wastewater, cultivated/constructed land, inversion, water consumption	Positive	More positive in neighboring cities with low industry if connected with high industry HSR cities
	Tang et al. (2023)	CO <sub>2</sub>	Positive	Positive in neighboring cities of service-dominated cities
	Li and Guo (2021)	COD, NH <sub>3</sub> N, SO <sub>2</sub> , and NO <sub>x</sub>	Negative	More negative in neighboring cities with a large number of industrial firms

	Jia et al. (2021)	CO <sub>2</sub>	Positive	Negative in neighboring areas of resource-based cities
<b>The Size of Cities</b>	Wei and Liu (2023)	CO <sub>2</sub> , SO <sub>2</sub> , PM <sub>2.5</sub> , NDVI, wastewater, cultivated/constructed land, inversion, water consumption	Positive	More positive in neighboring cities of large HSR cities
	Yan et al. (2023)	SO <sub>2</sub>	Positive	Positive in neighboring areas of small HSR cities
	Tang et al. (2023)	CO <sub>2</sub>	Positive	Positive in neighboring areas of large HSR cities
	Jia et al. (2021)	CO <sub>2</sub>	Positive	Negative in neighboring areas of large HSR cities
<b>Environmental / other transport policies</b>	Li and Guo (2021)	COD, NH <sub>3</sub> N, SO <sub>2</sub> , and NO <sub>x</sub>	Negative	More negative if HSR cities has higher levels of environmental investments

<sup>a</sup>The “Overall Impact” column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact varies in neighboring areas of the HSR network, the “Impact on Neighboring Areas” column specifies how these differences manifest.

Research indicates that the distance between HSR cities and their neighboring areas influences the environmental benefits derived from HSR operations. Generally, the closer neighboring cities are to the HSR city, the more significant the environmental benefits (see, for example, [Liu et al. \(2022b\)](#) and [Guo et al. \(2021\)](#)). Some studies explore the specific distance thresholds for observing the effects of HSR. [Nie and Zhang \(2023\)](#) suggest that HSR services improve the surrounding environment within a 300 km radius, with no significant effects beyond that distance. [Yu and Wan \(2022\)](#) find no substantial impact within 100 km of the HSR city, but they report a significantly positive effect beyond 200 km, which gradually decreases as the distance increases. [Jia et al. \(2021\)](#) state that the environmental impacts of HSR can be observed within 500 km of the HSR city. Within this range, HSR serves as a substitute for road transport. Interestingly, between 500 km and 1000 km, the impact first decreases and then increases, reflecting the indirect environmental effects of HSR and the transportation substitution effect related to air passenger transport. Beyond 1000 km, no impact from HSR is observed, as air transport becomes the dominant mode of travel.

Two studies analyze the spillover effects of HSR on two different types of neighboring cities: those with an HSR station and those without. [Tang et al. \(2023\)](#) argue that the operations of HSR improve the environments of neighboring cities with HSR stations compared to those without. This is because industrial resources tend to move from cities lacking HSR access to those with HSR stations, leading to enhanced resource allocation efficiency and a better-adjusted industrial structure in the HSR cities. Conversely, [Yan et al. \(2023\)](#) suggest that the spillover effect brings more environmental benefits for cities without an HSR station than those along the HSR line. The reason is that while modern service industries are concentrated in central cities along the HSR line, more polluting industries in these cities are often pushed into peripheral cities along the same line.

Some studies indicate that HSR operations in economically more developed cities can increase environmental pollution in neighboring areas. After HSR services begin, companies in developed areas often face stricter environmental regulations and may prefer to relocate to nearby regions with looser ones ([Li and Guo, 2021](#)). Additionally, these developed cities tend to draw resource endowments away from their neighboring areas, which can further degrade the environmental quality of those areas or hinder their environmental progress ([Gao and Wang, 2023](#)). Moreover, [Yan et al. \(2023\)](#) suggest that the environmental improvements associated with

HSR are more pronounced in economically developed neighboring cities because they are better able to leverage the knowledge spillover effects of HSR due to their greater financial resources to attract high-tech talent and businesses. Conversely, Yan et al. (2024) argue that if neighboring cities are more developed than the HSR city, there may be insufficient incentives for productive resources to move from the more affluent neighbors to the less developed HSR city. As a result, the environmental burden in these neighboring cities cannot be reduced.

The industrial structures of HSR cities and their surrounding areas influence the environmental impact of HSR operations on neighboring cities as well, as illustrated in Table 10. For instance, Jia et al. (2021) explore the mechanisms behind this relationship and propose that HSR operations could negatively impact the environment of nearby cities, particularly if HSR cities are dominated by resource-based industries. This is because polluting industries in HSR cities may relocate to surrounding areas.

The size of the HSR city and its neighboring cities is another factor influencing how HSR operations affect the environment in neighboring cities. Jia et al. (2021) and Yan et al. (2023) suggest that HSR operations can lead to increased environmental pollution in nearby areas of major HSR cities. This occurs because HSR accelerates the movement of production resources from neighboring cities to larger HSR cities, which can diminish resource efficiency and environmental quality in those neighboring areas. Moreover, these larger cities often serve as “business cards” for their regions, showcasing their economic and environmental attributes. After HSR services come into service, they may relocate lower-technology and highly polluting industries to their smaller neighbors. As a result, the environmental benefits of HSR on the neighboring cities tend to be greater for smaller HSR cities compared to larger ones (p. 11, Yan et al., 2023). In contrast, Tang et al. (2023) and Wei and Liu (2023) argue that HSR operations reduce environmental pollution in the surrounding areas of large HSR cities. Environmental quality in large HSR cities tends to deteriorate as they attract a mass flow of people from nearby areas once HSR operations begin. As a result, smaller neighboring cities connected to these larger HSR cities usually experience a more favorable environmental impact from HSR operations (Wei and Liu, 2023).

Finally, Li and Guo (2021) point out that the higher the per capita environmental investment in HSR cities, the more significant the negative effect is observed in neighboring cities, as polluting industries tend to relocate to regions with looser environmental controls and obligations.

### 3.1.3 Features of transport systems

The environmental impact of HSR varies depending on the characteristics of the transport system along HSR routes, as outlined below. Each study in [Table 11](#) reports this variation according to one or several different aspects simultaneously.

- Travel time/distance
- The Airlines' responses to HSR operations
- The volume of HSR operations
- Source of energy used by HSR
- Co-existing with conventional rail
- Environmental/other transport policies

Studies presented in [Table 11](#) demonstrate that travel time/distance influences the environmental impact of HSR because it affects how effectively HSR can substitute for other modes of transportation, thereby promoting the reduction of transport emissions. Among them, the study conducted by [Guo et al. \(2020\)](#) examines the extent to which HSR services substitute for passenger car travel and concludes that HSR positively contributes to reducing emissions, particularly when the travel time difference between HSR and private cars is over one hour. This is due to the fact that the substitution effect of HSR becomes more pronounced over such travel time differences. Other studies examine the extent to which HSR substitutes for air passengers' travel based on travel time/distance. They primarily indicate that HSR has significant potential to attract passengers from airlines for short distances, typically around 4–5 h, thereby reducing aviation-related emissions. Nevertheless, [Yuan et al. \(2023\)](#) highlight that the emission reduction effect due to the substitution of short-haul air travel by HSR seems not substantial, as long-haul flights are the major contributor to aviation emissions.

Additionally, some research indicates that other transport characteristics might alter the relationship between travel time/distance and the emission reduction effect of HSR operations. [Gu and Wan \(2022\)](#) point out that introducing HSR could lead to an overall increase in CO<sub>2</sub> emissions although HSR offers advantages over air travel when the difference in travel time between HSR and aviation is less than five hours. This increase may occur due to a rise in air travel demand, driven by better ground connections provided by HSR operations, or lower airfare prices resulting from competition between HSR and airlines. This could undermine the positive environmental benefits of HSR by diminishing the substitution

**Table 11 The environmental impact of HSR according to features of transport systems<sup>a</sup>.**

Article	Environmental Indicators	Overall impact	Travel time/ distance	Airlines' responses to HSR operations	The volume of HSR operations	The energy source used by HSR	Co-existing with Conven. rail	Environmental/ other transport policies
Yuan et al. (2023)	CO <sub>2</sub>	Positive	Positive over short distances					
Gu and Wan (2022)	CO <sub>2</sub>	Negative	Positive over short travel time difference	Depends on airfare adjustment and travel time				
Chen et al. (2022b)	CO <sub>2</sub>	Negative	Positive over short distances		Positive if the volume of HSR operations is larger			
Janić (2021)	CO <sub>2</sub>	Positive	Positive over short distances		More positive if the volume of HSR operations is larger			
Guo et al. (2020)	CO, PM <sub>2.5</sub> , and O <sub>3</sub>	Positive	Positive over longer travel time difference					More negative
Wang et al. (2019)	CO <sub>2</sub>	Positive	Positive over short distances				Depends on the mix of energy sources	

(continued)

**Table 11 The environmental impact of HSR according to features of transport systems<sup>a</sup>. (cont'd)**

Article	Environmental indicators	Overall impact	Travel time/ distance	Airlines' responses to HSR operations	The volume of HSR operations	The energy source used by HSR	Co-existing with Conven. rail	Environmental/ other transport policies
D'Alfonso et al. (2015)	Environmental Pollution	Mixed	Positive over short distances	Depends on flight frequency and travel time		depends on the mix of energy sources		
Prussi and Lonza (2018)	GHG	Positive	Positive over short distances					
Álvarez (2010)	CO <sub>2</sub>	Positive				More positive than other modes	less positive	
Sun et al. (2022)	Wastewater, SO <sub>2</sub> , and smoke	Positive			More positive if the volume of HSR operations is larger			
Yao et al. (2023)	CO <sub>2</sub>	Positive			More positive if the volume of HSR operations is larger			
Jiang and Liu (2022)	Soot, CO <sub>2</sub> , wastewater, power consumption, PM <sub>2.5</sub> , industrial solids, and the sewage treatment	Positive			More positive if the volume of HSR operations is larger			

Li and Guo (2021)	COD, NH3N, SO <sub>2</sub> , NO <sub>x</sub>	Negative	Positive if the volume of HSR operations is larger
Liu et al. (2022b)	AQI	Positive	More positive if the volume of HSR operations is larger
Rajendran and Popfinger (2022)	CO <sub>2</sub>	Positive	More positive if the volume of HSR operations is larger
Gan et al. (2020)	CO <sub>2</sub>	Negative	More negative if the volume of HSR operations is larger
Dalkic et al. (2017)	CO <sub>2</sub>	Positive	More positive if the volume of HSR operations is larger

(continued)

**Table 11 The environmental impact of HSR according to features of transport systems<sup>a</sup>. (cont'd)**

Article	Environmental indicators	Overall impact	Travel time/ distance	Airlines' responses to HSR operations	The volume of HSR operations	The energy source used by HSR	Co-existing with rail	Environmental/ other transport policies
Krishnan et al. (2015)	CO <sub>2</sub>	Positive			More positive if the volume of HSR operations is larger	Depends on the mix of energy sources		
Robertson (2013)	CO <sub>2</sub>	Positive			More positive if the volume of HSR operations is larger	Depends on the mix of energy sources		
Prussi et al. (2019)	GHG	Positive				More positive than aviation		
D'Alfonso et al. (2016)	HC, CO, NO <sub>x</sub> , SO <sub>2</sub> , PM, GHG	Mixed				depends on the mix of energy sources		
Boehm et al. (2021)	CO <sub>2</sub>	Positive						Mixed
Sun et al. (2020)	Wastewater, SO <sub>2</sub>	Positive					Less positive	
Strauss et al. (2021)	CO <sub>2</sub>	Positive						More positive
Yang et al. (2019)	SO <sub>2</sub>	Positive						More positive

Sun and Li (2021)	CO <sub>2</sub>	Positive	More positive
Chen et al. (2022a)	CO <sub>2</sub>	Positive	More positive
Li et al. (2022)	Wastewater, SO <sub>2</sub> , and dust	Positive	More positive
Liu et al. (2023)	COD, SO <sub>2</sub> , dust, and wastewater	Positive	positive
Su and Xie (2023)	PM <sub>2.5</sub>	Positive	More positive
Chen et al. (2023a)	Electricity consumption	Positive	More positive
Han and Wang (2023)	Green patents applications	Positive	More positive
Gao et al. (2022)	COD and SO <sub>2</sub>	No effect	No effect

<sup>a</sup>The “Overall impact” column summarizes the main message of the abstract and conclusions regarding the environmental effects of HSR operations. If the impact differs in accordance with specific features of transport systems, other columns specify how these differences manifest, related to these respective features.

effect from air travel or even increasing air traffic. Similarly, [Chen et al. \(2022b\)](#) state that traveling with HSR is more environmentally friendly than air travel only for short distances (around 400 km) with high travel demand. For longer distances (around 1700 km), air travel emits fewer emissions than HSR because airlines can use smaller vehicles and flexible frequencies to achieve high loads. [D'alfonso et al. \(2015\)](#) conclude that HSR services may result in a withdrawal of aircraft services on routes of less than 300 km, while HSR may compete with airlines on routes between 300 and 1000 km. In this competition, they conclude that airlines may operate with lower frequencies and smaller aircraft to achieve high loads. In such circumstances, the introduction of HSR services may only be beneficial to the environment in large travel markets. However, if HSR reduces travel time to attract air passengers by operating at a higher speed, the emission reduction effect of HSR services might potentially reduce as the energy consumption increases in parallel to the speed, particularly in countries such as China where the generation of electricity mainly relies on coal ([D'alfonso et al., 2015](#); [Prussi and Lonza, 2018](#)). Related to this, [D'alfonso et al. \(2015\)](#) and [D'alfonso et al. \(2016\)](#) note that airlines have the opportunity to switch to non-conventional jet fuels to diminish air-related emissions, but the source of electricity used by HSR is heavily constrained by the country in which HSR operates. Yet still, HSR operations already emit fewer emissions than airlines across various scenarios, and the environmental performance of HSR improves when the electricity supply for HSR operations is obtained from renewable sources ([Robertson, 2013](#), [Wang et al., 2019](#)). In fact, [Prussi et al. \(2019\)](#) conclude that HSR emits fewer GHG emissions per passenger kilometer, even when aviation utilizes biomass-derived fuel.

Most studies suggest that HSR has an increasingly positive influence on environmental quality as the volume of HSR services grows (e.g. a larger network, higher capacity, or more frequent services). A high volume of HSR operations makes the reduction in environmental pollution more significant by amplifying both the direct and indirect positive effects. This is supported by research conducted by [Sun et al. \(2022\)](#), [Yao et al. \(2023\)](#), and [Liu et al. \(2022b\)](#). Furthermore, some studies suggest that HSR operations can be harmful to the environment, yet this negative impact turns positive only when the HSR traffic volume is substantial. For instance, [Li and Guo \(2021\)](#) point out that industrial pollution can be transferred to the areas surrounding HSR cities, exacerbating their environmental quality. However, these surrounding cities can mitigate the

transmitted pollution when a dense and extensive rail network exists. A robust HSR network facilitates the mobility of people in search of better environments within the region, and they may advocate for stronger environmental regulations. Thus, this reduces the disparity in environmental standards among cities. [Chen et al. \(2022b\)](#) find that connecting small and remote cities with HSR is less environmentally friendly than air travel because airlines are more flexible in adjusting flight frequencies and passenger loads without the significant infrastructure and maintenance costs associated with the HSR network. However, they note that HSR connections to these cities can have a positive environmental impact when travel demand is high. Conversely, [Gan et al. \(2020\)](#) argue that HSR negatively impacts the environment, intensifying with an increasing volume of HSR services, as the emission reduction benefit of HSR operations due to modal shift is outweighed by the emissions increase resulting from urbanization and economic growth boosted by HSR services.

Some studies identify the interaction between HSR operations and various environmental regulations or pricing policies in improving environmental quality. The research indicates that HSR operations are more effective in reducing environmental pollution in regions with strict environmental regulations than in other areas. This is likely because businesses in regulated areas are more motivated to adopt environmentally friendly technologies, thus benefiting more from the favorable conditions created by HSR, including enhanced information flow or technology exchange ([Yang et al., 2019](#); [Su and Xie, 2023](#); [Li et al., 2022](#)). However, [Gao et al. \(2022\)](#) note that HSR's role in improving environmental quality is not significant, as the Chinese government already enforces environmental regulations effectively in these areas. Furthermore, some studies investigate how HSR operations affect the environment when implemented alongside pricing policies like carbon taxes or road tolls, which aim to mitigate the negative externalities of industry and transportation. Implementing pricing policies in parallel to HSR services influences the extent to which HSR services contribute to improving environmental quality because this may affect the substitution rate of HSR services. [Strauss et al. \(2021\)](#) conclude that a 35-dollar carbon tax promotes a modal shift from air travel to HSR, thereby reducing carbon emissions. [Boehm et al. \(2021\)](#) suggest that imposing a carbon tax of 100 EUR for transporting low-density, high-value goods by road is ineffective in enhancing the environmental impact of HSR unless HSR track-access charges and road

fees are adjusted accordingly. However, [Guo et al. \(2020\)](#) find that the environmental benefit of HSR on toll-free days, when highway traffic volume is higher, increases because of a larger substitution effect of HSR for road transportation on these days.

Finally, the research also highlights that HSR's environmental benefits decrease if HSR primarily competes with conventional rail in the same area and when the shift mainly comes from former conventional rail users rather than air or road transport ([Álvarez, 2010](#); [Sun et al., 2020](#)).

### 3.2 The lifetime environmental impact of HSR and variations in the payback time

[Table 12](#) presents studies that examine the lifetime environmental impact of HSR. These studies suggest that the construction phase of HSR projects puts a significant strain on the environment due to the extraction and consumption of large quantities of materials and energy resources, whereas HSR operations are associated with environmental benefits. They estimate the payback time for the total emissions involving an HSR project, considering construction, maintenance, and operations, and explore factors influencing the payback time of HSR projects. The last column of [Table 12](#) provides information on the payback time for HSR emissions, while the other columns present findings related to the factors affecting the duration of this payback period. Studies primarily focus on the lifetime impact of CO<sub>2</sub> and GHG emissions, with few addressing emissions of NO<sub>x</sub>, SO<sub>x</sub>, and PM.

The findings regarding the payback time of HSR projects show significant variation, with durations ranging from 6 to 100 years. This variation exists in terms of different emission types and even within the same type of emission. Such contradictory results likely stem from the fact that the studies evaluate various HSR projects and calculate emissions based on differing assumptions, such as future modal shares and ridership levels. Furthermore, differing payback periods for various emissions are typically due to the unique chemical characteristics of each and their interactions with other emissions.

On the other hand, the literature predominantly agrees on the key factors that influence the playback time of HSR emissions. The volume of HSR operations seems to be the most critical factor in determining the overall environmental benefits of HSR construction. Almost all studies emphasize that the payback time is shorter with a higher rate of modal shifts from carbon-intensive transport modes to HSR, higher levels of occupancy

**Table 12 The studies on the lifetime impact of HSR.**

Article	Environmental / other transport policies	Operations	The volume of HSR	Characteristics of HSR networks	Energy sources used by HSR	The tech. of HSR rolling stock	A payback time of life cycle emissions
Kortazar et al. (2023)			Longer if HSR traffic volume is lower	Shorter if the topography is less mountainous			GHG: 24 years, NMVOC: 12 years, PM <sub>10</sub> : 30 years
Damián and Zamorano (2023)			Shorter if modal shifts from polluting modes are higher		Shorter if more renewable energy sources are used		GHG: 19–23 years
De Bortoli and Féraïlle (2024)			Shorter if there is a short-haul flight ban	Shorter if modal shifts from polluting modes are higher	Shorter if more renewable energy sources are used		GHG: 10–60 years
Chen et al. (2021)			Shorter if modal shifts from polluting modes are higher				CO <sub>2</sub> : 26 years

(continued)

**Table 12 The studies on the lifetime impact of HSR. (cont'd)**

Article	Environmental / other transport policies	Operations	The volume of HSR	Characteristics of HSR networks	Energy sources used by HSR	The tech. of HSR rolling stock	A payback time of life cycle emissions
Kortazar et al. (2021)		Shorter if modal shifts are from polluting modes, longer if induced travel due to HSR is higher					GHG, CED, NO <sub>x</sub> , NMVOC: 9–16 years, SO <sub>2</sub> : 62 years, PM <sub>10</sub> : 87 years
Bueno et al. (2017)		Shorter if induced travel due to HSR is lower and modal shifts are from polluting modes		Shorter if the topography is less mountainous			CO <sub>2</sub> : never (even in 100 years)
Chang and Kendall (2011)		Longer if modal shifts from polluting modes are lower					GHG: 6 years
Chester and Horvath (2010)		Shorter if HSR occupancy is higher			Shorter if more renewable energy sources are used		GHG: 6–71 years, SO <sub>2</sub> : never

Chester and Horvath (2012)	Shorter if modal shifts from polluting modes are higher	Shorter if more renewable energy sources are used	GHG: 20–30 years, Acidification: 20–40 years
Robertson (2018)	Shorter if modal shifts from polluting modes are higher	Shorter if more renewable energy sources are used	CO <sub>2</sub> : annual reduction throughout the longitudinal period
Robertson (2016)	Shorter if modal shifts from polluting modes are higher	Shorter if more renewable energy sources are used	Shorter if CO <sub>2</sub> : annual reduction throughout the longitudinal period HSR rolling stock is more advanced
Åkerman (2011)	Shorter if modal shifts from polluting modes are higher	Shorter if more renewable energy sources are used	GHG: annual reduction throughout the longitudinal period

(continued)

**Table 12 The studies on the lifetime impact of HSR. (cont'd)**

Article	Environmental / other transport policies	Operations	The volume of HSR	Characteristics of HSR networks	Energy sources used by HSR	The tech. of HSR rolling stock	A payback time of life cycle emissions
Chapindula et al. (2022)							GHG, CO <sub>2</sub> , NO <sub>x</sub> , SO <sub>x</sub> : not reported explicitly, but lower than PM
Chang et al. (2019)		Shorter if modal shifts from polluting modes are higher				GHG: not reported explicitly	
Matute and Chester (2015)		Shorter if modal shifts from polluting modes are higher				GHG: not reported explicitly	
Westin and Kägeson (2012)		Shorter if modal shifts from polluting modes are higher, HSR traffic volume is higher	Shorter if the topography is less mountainous			CO <sub>2</sub> : not reported explicitly	

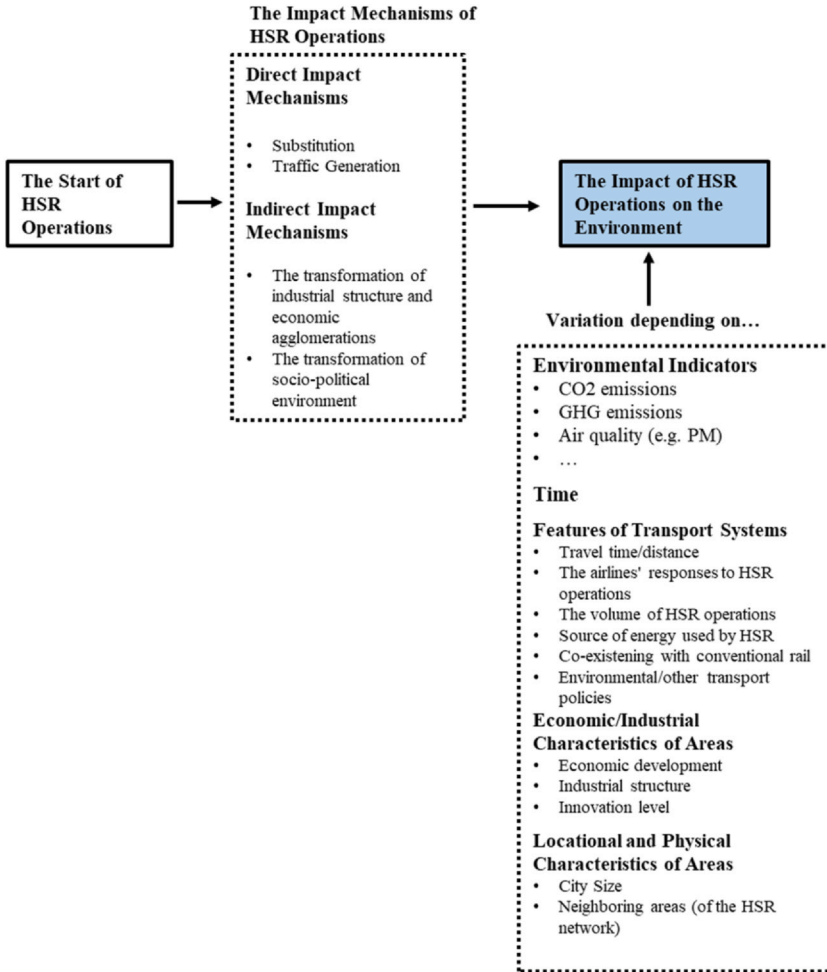
or ridership, and lower levels of induced travel due to HSR. Conversely, the payback time extends when induced travel due to HSR is higher. Moreover, most studies underline the significance of utilizing renewable energy sources to generate the electricity consumed by HSR. When more renewable energy sources are used in electricity production, the emissions from HSR operations decrease, resulting in a shorter payback time. The payback time is also reduced if HSR rolling stock is technologically advanced, as it lessens energy consumption related to HSR operations. Furthermore, HSR construction in mountainous regions entails complex structures, such as tunnels and viaducts, which may prolong the payback time by increasing environmental impacts during the construction phase. Lastly, policies such as a short-haul flight ban help shorten the payback time by encouraging modal shifts to HSR.



## 4. Discussion and conclusions

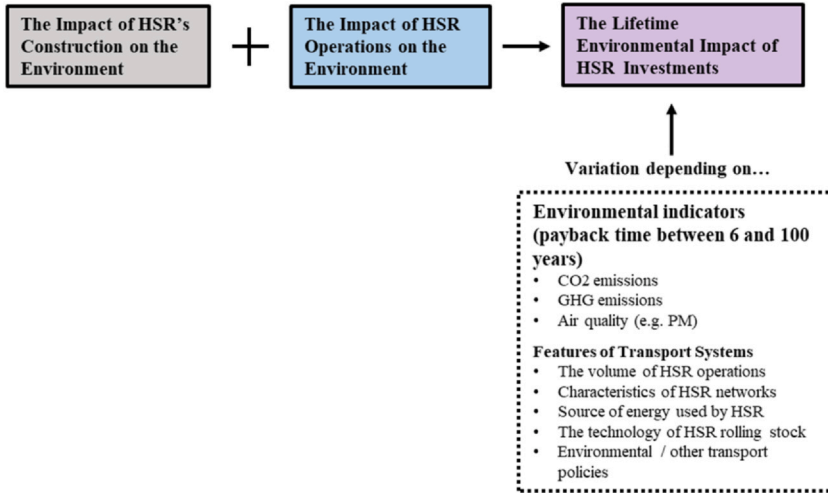
This study aims to conduct a comprehensive literature review to investigate the environmental impacts of HSR by examining the factors that influence the nature (i.e., negative or positive) and magnitude of these impacts, as well as the mechanisms through which HSR affects the environment. Our review has identified two lines of research. The first one focuses on the environmental effects of HSR operations. The second explores the lifetime environmental impact of HSR, including emissions released during operations and those generated during the construction, manufacturing, and maintenance phases of HSR projects. We incorporate the findings of these studies into two different frameworks, illustrated in Figs. 3 and 4. Fig. 3 summarizes the findings of the first one, illustrating the mechanisms related to the environmental impact of HSR operations and the factors that lead to variations in the environmental effects of HSR operations. Fig. 4 outlines the lifetime environmental impact of HSR. This includes not only the environmental effects of HSR operations but also those resulting from the construction and manufacturing phases of HSR projects. Additionally, it presents the factors that contribute to variations in the lifetime environmental impact of these projects.

Fig. 3 illustrates two types of impact mechanisms involving the environmental effects of HSR operations. The first one is the direct impact mechanisms that occur through the substitution effect and the traffic generation effect of HSR. The net effect depends on how many passengers



**Fig. 3 The framework of the environmental impact of HSR operations.**

from other modes are shifted to HSR (substitution effect) and how much new travel demand is generated by the HSR. While most studies consider only the substitution effect, only a few investigate the induced traffic by HSR or both. The findings indicate that while the increased rates of the substitution effect of HSR enhance the positive environmental impact, the higher rates of induced travel demand have the opposite effect, resulting in a negative environmental impact. The second one is the indirect impact mechanisms that include the transformation of industrial structure and economic agglomerations along the rail route and a change in the



**Fig. 4 The framework of the lifetime environmental impact of HSR investments.**

sociopolitical environment. They can make either a negative or a positive impact on the environment. Positive impact occurs in the following way: The opening of HSR provides time-space convergence by improving the accessibility between areas connected by HSR. Such convergence between cities facilitates the flow of resources and the diffusion of knowledge and technology between them. Such circumstances lead to (1) an increase in the production efficiency of enterprises, (2) the development of green technologies used in industrial firms, (3) the development of less polluting industries, such as service and knowledge-based industries, (4) an increase in environmental awareness that encourage firms to minimize the adverse effects of their operations and governments to strengthen environmental regulations. As such, such changes in the structure of industrial agglomerations and the social environment enable the reduction of industrial emissions over time. On the other hand, negative environmental impact results from such a process: the introduction of HSR increases accessibility and intensifies economic agglomeration, industrial energy consumption, and land development, which leads to higher polluting emissions. Furthermore, more polluting industries migrate to other regions, thereby shifting pollution to other places.

Our review indicates that HSR operations do not always lead to positive environmental outcomes, even though HSR generally produces lower emissions per passenger kilometer than other transport modes.

Approximately 50 % of studies examining the lifetime environmental impact and 15 % of those focusing on the environmental effects of HSR operations conclude that the overall environmental impact of HSR is not positive. Furthermore, most studies emphasize that the environmental effects vary based on several factors, even when they conclude that the overall environmental impact of HSR is positive. This is noteworthy since HSR typically generates lower emissions per passenger kilometer than other transport modes, and policymakers often consider HSR an environmentally friendly mode of transportation. Studies examining the lifetime environmental impact of HSR are generally less favorable than those that focus on HSR operations. This difference can be attributed to the fact that the non-operational phases of HSR, such as construction, manufacturing, and maintenance, have more negative environmental impacts than the operational phase of HSR. [Figs. 3 and 4](#) illustrate that the factors influencing the environmental impact of HSR discussed in both groups of studies largely overlap as expected, since studies using a lifetime perspective also analyze the impacts of HSR operations. However, the lifetime impact studies include fewer factors, which may be attributed to the smaller number of studies in this group.

The review does not show any clear trends regarding the nature (positive or negative) and magnitude of the environmental impact associated with these factors. Similarly, we cannot identify which impact mechanisms are dominant under which specific conditions. This is due to conflicting findings and the explanation of similar results through different impact mechanisms. Such contradictory findings likely arise from either methodological differences between studies or from analyzing only one or a few isolated factors, even though the environmental impact of HSR involves complex interactions among various social, economic, political, locational elements, and characteristics of transport systems. To clarify the complex relationships and interactions among these factors, further research should incorporate as many factors as possible, illustrated in [Figs. 3 and 4](#), into their analysis related to the environmental impact of HSR. Additionally, most studies rely on cases from China. More cases from Western countries should be investigated, as China differs significantly from Western countries not only in its political and economic environment but also in its cultural, geographic, and transportation structures. Furthermore, many studies that consider a lifetime perspective on HSR seldom account for factors such as the locational, physical, social, and economic characteristics of the areas, even though these factors likely influence the

payback period of HSR investments, as they contribute to differences in the environmental effects of HSR operations.

In conclusion, this chapter helps to understand the relationship between HSR and the environment and provides a comprehensive framework for future research in this area. Furthermore, this review highlights the importance of conducting a case-by-case analysis when evaluating HSR's environmental impact. The total environmental benefits of HSR may vary depending on many factors, even though HSR is more environmentally friendly per passenger kilometer than other transport modes.

## Declaration of AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used “Grammarly” in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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