High-speed Railway 1 (2023) 195–203

Contents lists available at ScienceDirect

High-speed Railway

journal homepage: www.keaipublishing.com/en/journals/high-speed-railway

Research article

Carbon emissions reduction potentiality for railroad transportation based on life cycle assessment

Yintao Lu[a,b,c], Tongtong Zhang[a,b,c], Shengming Qiu[a,b,c], Xin Liu[d], Xiaohua Yu[a,b,c], Hong Yao[a,b,c,*]

[a] School of Environment, Beijing Jiaotong University, Beijing 100044, China
[b] Intelligent Environment Research Center, Beijing Jiaotong University, Beijing 100044, China
[c] Engineering Research Center of Clean and Low-carbon Technology for Intelligent Transportation, Ministry of Education, Beijing Jiaotong University, Beijing 100044, China
[d] China Railway Beijing Group Company Limited, Beijing 100089, China

ARTICLE INFO

Keywords:
Life cycle assessment
High-speed-rail
Transportation structure
Intercity transportation
Carbon emission reduction potentiality

ABSTRACT

This study addresses the comparative carbon emissions of different transportation modes within a unified evaluation framework, focusing on their carbon footprints from inception to disposal. Specifically, the entire life cycle carbon emissions of High-Speed Rail (HSR), battery electric vehicles, conventional internal combustion engine vehicles, battery electric buses, and conventional internal combustion engine buses are analyzed. The life cycle is segmented into vehicle manufacturing, fuel or electricity production, operational, and dismantling-recycling stages. This analysis is applied to the Beijing-Tianjin intercity transportation system to explore emission reduction strategies. Results indicate that HSR demonstrates significant carbon emission reduction, with an intensity of only 24 %–32 % compared to private vehicles and 47 %–89 % compared to buses. Notably, HSR travel for Beijing-Tianjin intercity emits only 24 % of private vehicle emissions, demonstrating the emission reduction benefits of transportation structure optimization. Additionally, predictive modeling reveals the potential for carbon emission reduction through energy structure optimization, providing a guideline for the development of effective transportation management systems.

1. Introduction

Studies show that transportation has an important contribution to air pollution and Greenhouse Gas(GHG) emissions [1]. With the rapid development of the world economy, the share of carbon emissions originating from transportation in the overall carbon emissions has grown significantly and exceeded 25 % in recent years [2]. More specifically, carbon emissions caused by the transportation sector account for over 10 % of total carbon emissions in China. It is noting that these emissions are dominated by road transportation, which is predicted to reach its peak after 2040 [3]. Although the share of railroad, waterway, and pipeline transportation in the transportation of passengers and cargo has increased in recent years, the dominance of road transportation still persists. For instance, the freight turnover of China's road transportation in 2020 exceeded that of railroad transportation by 1.97 times, with the number of passengers for roads surpassing rail by 3.13 times [4]. Railroad transportation has superior characteristics, including low carbon emissions. Based on investigations, carbon emissions per unit cargo in rail transportation is only 5.09 % of that of highway transportation [5]. However, a comprehensive investigation is required to fully determine the exact advantage of rail transportation over highway transportation over the whole life cycle of the railroad. Meanwhile, a comparative study of the full life-cycle carbon emissions across rail and other modes of transportation is a fundamental issue for profoundly understanding transportation restructuring.

Numerous investigations have focused on Life Cycle Analysis (LCA) to evaluate carbon emissions in railroads. These analyses encompass both the infrastructure and operation periods as a life cycle. For instance, Ref. [6] conducted an LCA evaluation covering the construction and operation phases of highways and HSR in Turkey. Based on the characteristics of railroad construction, Ref. [7] calculated carbon emissions for the construction phase of a project located in Zhengzhou, China. Moreover, Ref. [8] proposed a method for measuring energy consumption and carbon emissions during the construction phase of High-Speed Rail (HSR) infrastructure. Ref. [9] employed eBalance software and analyzed the difference between the whole life cycle in

* Corresponding author.
E-mail address: hyao@bjtu.edu.cn (H. Yao).

https://doi.org/10.1016/j.hspr.2023.08.004
Received 17 August 2023; Received in revised form 25 August 2023; Accepted 30 August 2023
Available online 1 September 2023
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evaluating the HSR and ordinary railroad. Ref. [10] conducted experiments and revealed that the environmental impact of highways in the infrastructure construction phase is about 10 % of that attributed to HSR. Ref. [11] employed the LCA method to predict the net carbon dioxide emissions of the Beijing-Shanghai HSR in an ex-post evaluation.

The aforementioned studies predominantly focus on the infrastructure construction and operation phases within the life cycle. However, further investigations revealed that the impact of transportation vehicles on the life cycle of the railroad should also be considered in calculations. This is because transportation vehicles have a relatively shorter lifespan in comparison to the infrastructure components. Currently, there are limited studies focusing on the whole life cycle carbon emissions of railroad vehicles. In this context, Ref. [12] and Ref. [13] analyzed the whole life cycle emission characteristics of Beijing-Shanghai trains using different LCA evaluation methods. However, these investigations exhibit variations in evaluation boundaries and methods and show that each transportation mode has a different life cycle, thereby increasing deviations in the evaluation results. Consequently, it is of significant importance to analyze HSR trains and road transport vehicles within the same statistical framework and evaluation boundary to comprehensively understand the advantages of carbon emission reduction in rail transportation.

To gain a profound comprehension of the matter, this study unifies the evaluation boundaries of the whole life cycle of railroads and road vehicles, analyzes their environmental impacts and carbon emission intensities, and compares the carbon emissions of specific transportation routes. The subsequent sections of this article are organized as follows: Section 2 introduces the passenger traffic and the vehicle LCA model. In Section 3, the environmental impact characteristics of different types of vehicles are analyzed and the carbon reduction potential of HSR transportation is discussed. Finally, the main achievements are summarized in Section 4.

2. Research methodology

2.1. Whole life cycle carbon accounting

2.1.1. Scope of the study and system boundaries

The main objective of vehicle lifecycle assessment is to comprehensively evaluate the environmental impact of HSR, electric vehicles, traditional cars, and electric and traditional buses from cradle to grave. To simplify calculations, GHGs like Methane (CH_4) and Nitrous Oxide (N_2O) are converted to Carbon Dioxide (CO_2) equivalents based on their warming potentials. Subsequently, the environmental impact of each mode of transportation is comprehensively analyzed according to the overall environmental impact potential of several vehicles over their lifecycles.

Based on the total life cycle research methodology, the total life cycle of a vehicle can be divided into four phases: the vehicle manufacturing phase (acquisition of raw materials, manufacturing vehicle body and manufacturing, and final assembly), the fuel or electricity production phase, the operational use phase, and the dismantling and recycling phase. These phases are schematically presented in Fig. 1.

2.1.2. Functional unit

Functional units are commonly used in LCA studies to quantify and measure product system performance. Consequently, the selection of functional units is of significant importance in ensuring the comparability of different LCA studies [14]. In comparative studies in the field of transportation, a typical functional unit is defined as the distance traveled. However, this criterion is usually applicable when vehicles have the same load capacities, while the vehicles and buses selected in this study have different load capacities compared with the HSR. Therefore, the present study considers the distance traveled by the vehicles of "1 passenger kilometer (pkm)" as the functional unit. The HSR locomotive has a service life of 20 years, and an average daily mileage of 1800 km [15]. Furthermore, the functional unit of cars is assumed to be 200000 km [16–18], and the functional unit of buses with an operational life span of 8 years and an average daily mileage of 180 km is 525600 km [19].

2.1.3. Life cycle inventory

In addition to HSR, four models including Internal Combustion Engine Vehicle (ICEV), Battery Electric Vehicles (BEV), Diesel engine Bus (DEB) and Electric Bus (EB) have been studied. The Life Cycle Inventory (LCI) involves a comprehensive analysis of inputs and outputs associated with products over their life cycle. This covers all materials and processes related to vehicle production, fuel/electricity production, operational usage, and dismantling and recycling processes. The data required for the production, usage, and end-of-life phases for conventional internal combustion engine vehicles, electric vehicles, and conventional and electric transit buses were collected from various sources including articles [11–13], GREET modeling databases eccointvent/ELCD, and USLCI databases. In evaluating the complete life cycle of HSR, this study focuses on the CRH380B train model, which comprises 16 carriages and weighs 980 tons. This model operates at an average distance of 900 km per single train run with two round trips per day. Additionally, representative automobiles and buses were selected as research objects based on 2020 automobile market sales data and the current operational bus models. The key parameters of the vehicles are provided in Table 1.

1) Vehicle manufacturing

The process of vehicle manufacturing involves various processes, including processes associated with raw material extraction (e.g., mining, smelting, and refining), component manufacturing, and assembly processes. During vehicle production, various subcomponents such as chassis, powertrain, driveline, traction motors, batteries and related fluids, and vehicle assemblies should be manufactured. Each subsystem is made of different materials as listed in Table 2. In this study, the power density of lithium iron phosphate batteries was assumed to be 140 kWh/kg and the battery weight was calculated based on the power cell capacity [20]. The overall production process of each type of vehicle is modeled using data from sources like Argonne Laboratories [17,19,21].

The vehicle assembly process includes painting, material handling, heating, and welding, all of which consume energy and produce emissions. It should be indicated that energy consumption during the assembly process is typically estimated proportionally to the vehicle mass. In this article, the average electricity and heat energy consumptions during the assembly process for various vehicles are approximated ranging from 17400 kJ/kg to 22100 kJ/kg as shown in Table 3[22].

2) Fuel production and manufacturing

The data for the electric power manufacturing stage was obtained from SimaPro's internal database, while the efficiency of the electric vehicle power battery was assumed to be 90 % [22]. Gasoline production mainly consists of four phases: extraction of crude oil, crude oil transportation, gasoline production, and gasoline transportation to gas stations. The energy consumption and emissions in gasoline production were calculated using the relevant database [23]. It takes 12936.38 MJ, 1101.02 MJ, 4543.55 MJ and 7291.80 MJ of energy to produce 1 kg of Fossil fuel, Coal, Petroleum and Natural gas, respectively. Due to the lack of data, gasoline data was also applied to diesel during the production stage.

3) Vehicle operation stage

Electricity consumption during the life cycle of an HSR, which is provided by the grid, can be obtained from Eq. (1).

$$E_{yy} = \sum_{t=1}^{T} q(t)\cdot e(t)\cdot R(t) \tag{1}$$

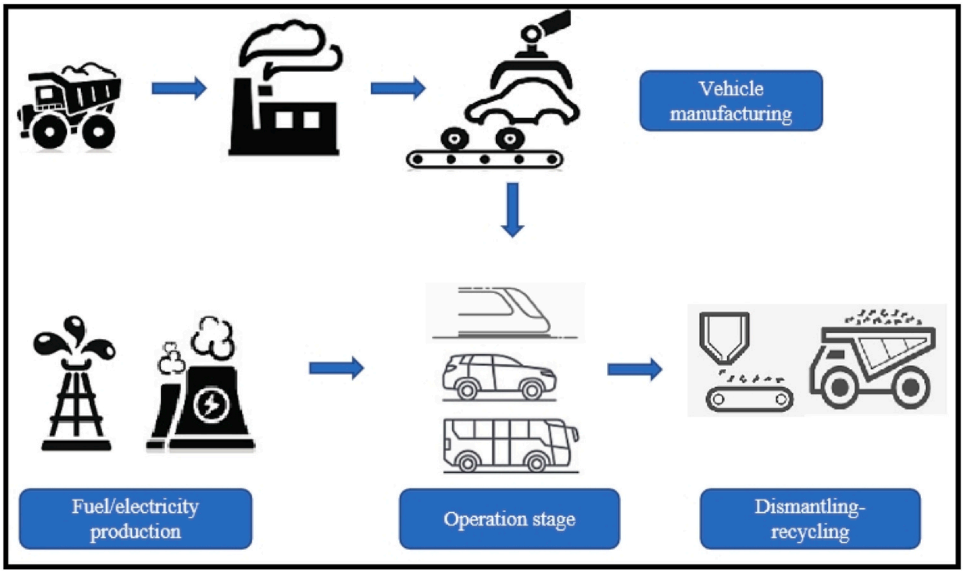

Fig. 1. Life cycle assessment boundary.

where E_{yy} represents the total electricity consumption over the entire life cycle of the railroad; $q(t)$ is the passenger capacity at period t of railroad operation; $e(t)$ is the unit transportation distance at period t, measured in km; $R(t)$ is the unit transportation electricity consumption at period t, expressed in km h km^{-1} per person; T is the full life cycle of HSR. Table 4 presents the unit consumption of HSR under different load factors at an operating speed of 300 km/h. In this article, an acceptable criterion of 85 % consumption was adopted.

The operation stage of conventional internal combustion engine vehicles corresponds to the "fuel pump" to the "wheel", encompassing the fuel cycle. During this phase, the environmental impacts involve the energy consumption and pollutant emissions caused by the direct combustion of fuel to power the vehicle or the electricity consumed by electric motors. In this study, the fuel or energy consumption in this stage was determined by multiplying the 100 km fuel or electricity consumption of the vehicle by the total distance driven before the vehicle is scrapped. So, ICEV and DEB use 0.058 L and 0.38 L of gasoline, respectively. BEV and EB use 0.118 kWh and 0.55 kWh of electricity, respectively. It is worth noting that electric vehicles consume electricity in the use phase and do not produce exhaust gases. Accordingly, this aspect of the carbon emissions is attributed to the electricity production phase, resulting in zero carbon emissions during the use phase of electric vehicles.

4) Vehicle dismantling-recycling

The electric vehicle dismantling-recycling stage can be primarily categorized into vehicle body crushing, battery treatment, and partial metal recycling. In this paper, it is assumed that only electric energy is consumed in the recycling phase, and the specific energy consumption of vehicle body crushing and battery recycling is 0.37 MJ/kg and 31 MJ/kg, respectively [24]. The scrapped vehicles undergo a series of mechanical treatments like disassembly, crushing, cleaning, and classification, and the separated waste materials such as copper, iron,

Table 2
Composition of materials for each type of vehicle %.

Material	HSR	ICEV	BEV	CDEB	BEB
Steel	49.5	59.9	43.9	57.7	47.5
Cast iron		1.9	0	9.2	7.6
Aluminum	13.8	4.6	2.3	11.8	9.7
		8.2	8.1		
Copper	5.3	2.4	4.8		
Magnesium		0	0		
Glass	7.7	2.4	1.7	5.1	4.2
Average plastic	23.8	15.3	10.7	12.3	10.1
Rubber		3.9	2.5	2.0	1.7
Glass fiber plastics		0.9	0.4		
Liquid		2.1	1.7	1.0	0.8
Lithium-ion battery			22.1		18.4

Table 3
Average energy consumption during the vehicle assembly process kJ/kg.

Energy type	ICEV	BEV	CDEB	BEB
Electricity	12896	15108	116525	114550
Heat	12896	15108	116525	114550

Table 4
Unit consumption of HSR under different load factors at an operating speed of 300 km/h.

Project	Value			
Load factor/%	40	70	85	100
Unit consumption/ (kWh/pkm)	0.093	0.053	0.043	0.037

Table 1
Main vehicle parameters.

Type of vehicle	Type of driver	Unladen mass/km	Mileage/km	Power cell	Mass of power cell /kg
HSR	Electric motor	980000	-	-	-
ICEV	Gasoline engine	1306	200000	-	-
BEV	Electric motor	1530	200000	Lithium-ion battery	335
DEB	Diesel engine	11200	525600	-	-
EB	Electric motor	11600	525600	Lithium-ion battery	2340

aluminum, and steel are smelted to be used as raw materials. The recovery rates for steel, iron, aluminum, and copper after dismantling the vehicle body are 90 %, 80 %, 92 %, and 90 %, respectively [25]. Due to limited data, the unit energy consumption in the dismantling stage of the HSR train is assumed to be equivalent to that of automobiles.

2.2. Life cycle impact assessment

The main objective of LCIA is to comprehend and quantify the potential environmental impacts of a product/service throughout its life cycle. In this study, the full LCA was conducted using Simapro 9.1 software, and the life cycle inventory data were obtained from LCA databases like ecoinvent/ELCD and USLCI databases. To achieve a full LCA evaluation, impacts were calculated based on impact factors calculated according to the ReCiPe 2016 Midpoint (H) evaluation methodology. This approach is widely used to determine impacts in various categories, including Global Warming Potential (GWP), Ozone Human Damage (OHD), Fine Particulate Matter Formation (FPMF), Terrestrial Ecotoxicity (TE), Terrestrial Acidification (TA), and Fossil Depletion (FD).

2.3. Prediction method of carbon emissions for the Beijing-Tianjin intercity transportation

2.3.1. Passenger capacity analysis

The predominant modes of intercity travel between Beijing and Tianjin primarily consist of highways and railroads. Yu [26] indicated that among various travel modes from Tianjin to Beijing in 2017, roads accounted for 53 % followed by the railroad with a contribution of 47 %. Li [27] employed statistical methods based on passenger ticket data and predicted that the passenger share of the Beijing-Tianjin intercity railway will increase to 63 % in 2025. The Beijing-Tianjin intercity railway is characterized by a large transportation volume, high train density, and bus development. Additionally, its fast, safe, and comfortable service has attracted a large number of passengers. Despite the increasing intercity HSR passenger traffic, Fig. 2 illustrates that road transportation still holds a large share of the overall intercity traffic.

In the long run, passenger traffic value increases linearly over time. So, the linear regression method was applied to fit the passenger traffic development in this study (Fig. 3). Based on the passenger traffic data from 2008 to 2019, establish a linear relationship between passenger traffic and time. It was calculated that passenger traffic after 2020 through this linear relationship. By comparing with the actual passenger Calculate from 2020 to 2022, this linear relationship is established. The emission model was established based on the turnover method to calculate the passenger carbon emissions of the Beijing-Tianjin intercity railway.

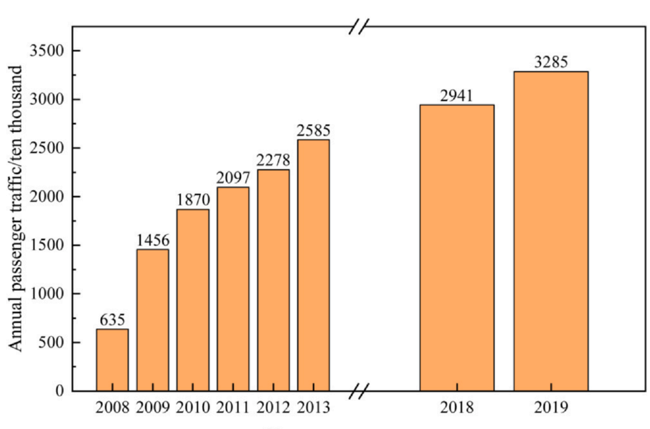

Fig. 2. Beijing-Tianjin intercity route passenger traffic.

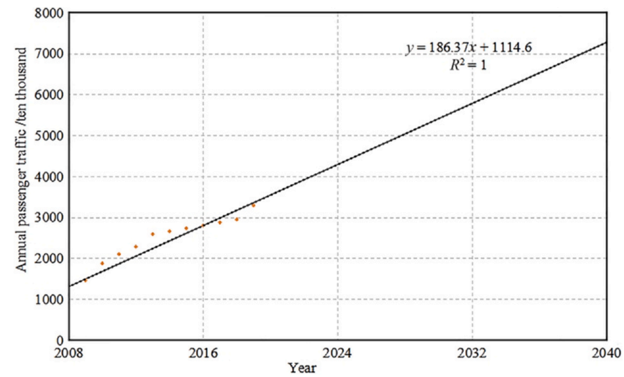

Fig. 3. Prediction of passenger traffic on Beijing-Tianjin intercity routes based on data from previous years.

2.3.2. Prediction model of carbon emission

According to “IPCC Guidelines for National Greenhouse Gas Inventory”, the carbon emission from transportation activity can be obtained from Eq. (2).

$$E_i = T_i \times q_i \quad (2)$$

where E_i is the carbon emission of transportation mode i, in $kgCO_2eq$; q_i is the unit carbon emission of transportation mode i, in $kgCO_2eq/pkm$; T_i is the transportation distance of transportation mode i, in pkm.

2.3.3. Influence factor analysis

The present study employs the energy mix of China in 2020 to calculate the whole life cycle carbon emissions of vehicles. The carbon emissions from the power generation process are very different across various energy structures [28]. According to the bulletins issued by the National Energy Administration and the National Bureau of Statistics, as well as the estimated results based on the national energy and electricity development strategy goals, GHG emissions from electric vehicles are predicted in Fig. 4. Accordingly, recommendations for the development of electric-driven vehicles will be made.

To facilitate energy conservation within traditional internal combustion engine vehicles and facilitate adjustments in transportation structure, the latest mandatory national standard "Fuel Consumption Limits for Passenger Cars" (GB 19578-2021) was officially implemented on July 1, 2021. This standard mandates that the average fuel consumption of new passenger cars should be reduced to 4.0 L/100 km by 2025 [29]. "Technology roadmap for energy saving and new energy vehicles 2.0 " predicts that the fuel consumption of passenger cars will decrease by 15–20 % by 2030 compared to the 2019 levels. Furthermore, it anticipates a similar reduction by 2035 [30].

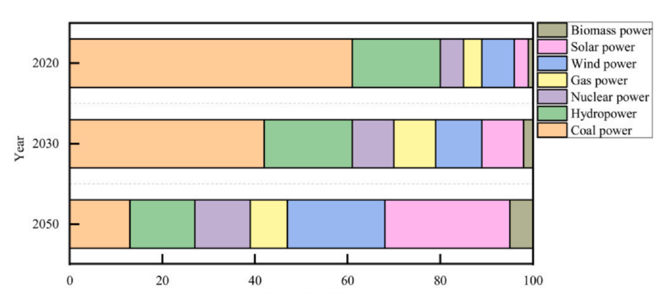

Fig. 4. Electric power structure of China in 2020, 2030, and 2050.

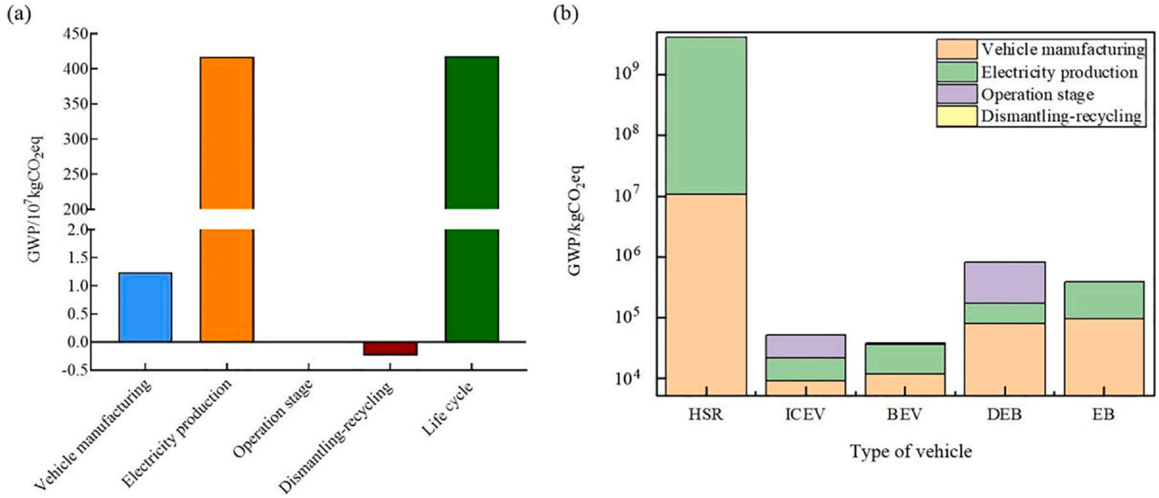

Fig. 5. The carbon emission for SHR and various types of vehicles: (a) carbon emission for each process of SHR; (b) carbon emission for the whole life cycle of vehicles.

3. Results and discussions

3.1. Characteristics of carbon emissions and environmental impacts for the different types of vehicles

Fig. 5(a) indicates that the total carbon emission across the entire life cycle of HSR trains is 4.18×10^9 kgCO$_2$eq, of which the vehicle manufacturing stage accounts for only 0.3 %. While numerous investigations on the full life cycle evaluation of HSR encompass the infrastructure and station operation components, calculating the full life cycle carbon emissions involves infrastructure, station operation, and the operation of 1625 trains over a span of 100 years. The operation cycle contributes to 93 % of the energy consumption and carbon emissions [24]. Existing studies on the full life cycle evaluation of HSR indicate that carbon emissions primarily originate from the operation phase of railroad trains. It should be indicated that the present study only analyzes a single HSR train. The continuous upgrading of HSR technology and the rapid expansion of the HSR network may yield variances among research cases.

As depicted in Fig. 5(b), the whole life cycle of vehicle manufacturing and operation indicates that HSR exhibits higher carbon emissions compared to other types of vehicles. This may be attributed to the high passenger capacity of HSR and its large size of carriage. In the case of conventional vehicles and buses, those powered by electricity show a reduction in carbon emissions by 27 % and 49 %, respectively, as compared to conventional ICEV. The emission reduction predominantly originates from the fuel production stage and the operation stage, where electricity exhibits obvious emission reduction potential compared to traditional energy sources. During the vehicle manufacturing stage, BEV and EB demonstrate higher carbon emissions compared to traditional internal combustion engine vehicles and diesel buses by 1365 kgCO$_2$eq and 6359 kgCO$_2$eq, respectively. The difference may be attributed to the higher overall weight of BEV and EB. Meanwhile, their batteries are made from a diverse range of materials and involve more intricate processes, thereby consuming additional energy during production.

Fig. 6 illustrates the results of the environmental impact inventory for the whole life cycle of various types of vehicles. With the exception of terrestrial ecotoxicity, the environmental impacts of internal combustion engine vehicles of the same type are notably higher than those of electric vehicles. Moreover, the standardized comprehensive environmental impact of ICEV across the whole life cycle is 1.4 times

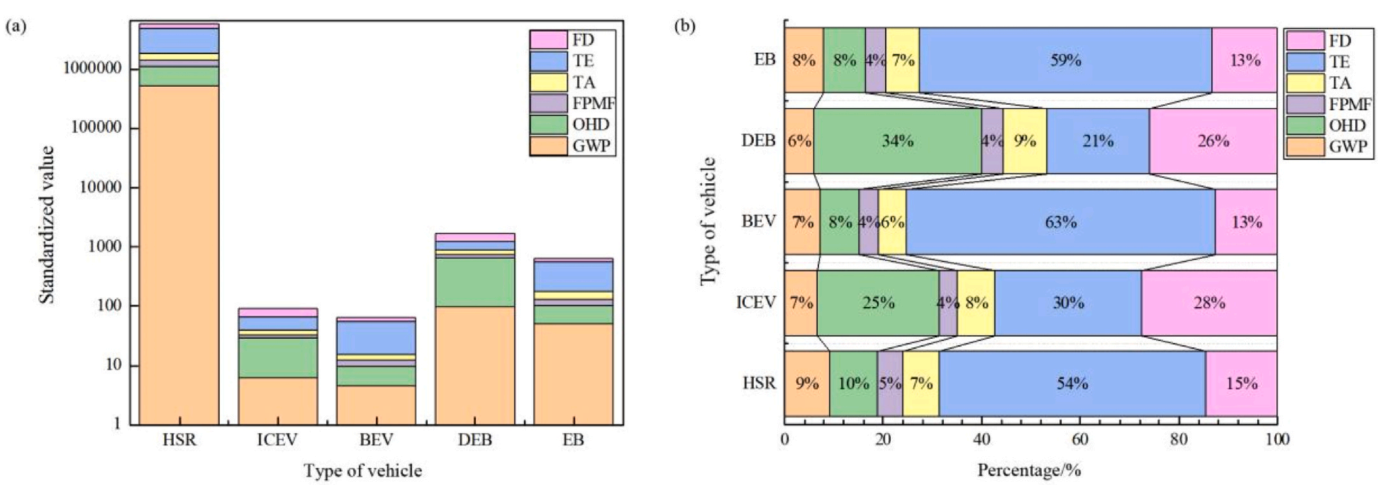

Fig. 6. Environmental impacts for the whole life cycle of vehicles: (a) environmental impacts of each type of vehicle; (b) proportion of environmental impacts of each type.

greater than that of BEV. Additionally, the comprehensive environmental impact of electric buses is merely 38 % of that of traditional buses. The analysis demonstrates that electric-powered vehicles outperform conventional buses in terms of carbon emissions and contribute to an overall reduction in comprehensive environmental impact. Studies show that vehicles significantly contribute to environmental concerns such as GHGs, global warming, photochemical ozone synthesis, and acidification problems originating from the use of fossil fuels. The results of the present article align with previously published articles [14,25,31–35].

Since the service life, train volume, and passenger traffic during the life cycle of an HSR train are much larger than those of other vehicles, the carbon emissions and environmental impacts of a railroad train over its entire life cycle are relatively large. However, the carbon emissions should be analyzed per unit of transportation volume for various modes of transportation.

3.2. Carbon emission intensity for the different types of vehicles

In transportation activities, higher load factors correspond to increased transportation capacity, subsequently yielding greater environmental benefits (while ignoring the increase in fuel consumption associated with higher vehicle weight). Therefore, establishing an appropriate load factor is of significance importance for resolving variations in the carbon emission intensity among diverse transportation modes. In this investigation, an average full load factor of 85 % is assigned to HSR locomotives, while ordinary passenger vehicles typically carry an average passenger load factor of 1.6p [36]. City bus passenger capacity, as outlined in the "Technical Specifications for Safety of Power-Driven Vehicles Operating on Roads," is calculated at 0.125 square meters per person. However, actual operational capacities often falls below this standard. According to China EV100 data, buses accommodate around 24 individuals, with an average full load rate set at 80 % for analyzing carbon emissions per bus unit. The carbon emission intensity per unit of transportation for each mode is calculated using Eq. (3).

$$EF_i = E_i / Q_i / e_i \tag{3}$$

where i is transportation mode; EF_i denotes carbon emission intensity of unit traffic volume, in $kgCO_2eq/pkm$; E_i represents the total carbon emission of the whole life cycle of the vehicles, in $kgCO_2eq$; Q_i is the number of individuals engaging in transportation, measured in persons; e_i is transportation distance of vehicles, measured in km.

The carbon emission intensity per unit and the normalized environmental impact per unit for HSR trains are notably lower compared to automobiles, constituting only 24–32 % of the latter, and lower than buses, ranging from 46 % to 89 % (as depicted in Fig. 7). The analysis conducted above demonstrates that, given the current full load factor, whether for short urban trips or medium-to-long-range transportation needs, the HSR mode of travel demonstrates a pronounced emission reduction advantage in the transportation sector. This observation is in line with the findings of Lin et al. [37].

3.3. Emission reduction analysis for the Beijing-Tianjin intercity transportation

3.3.1. Scenarios for transportation structure of Beijing-Tianjin intercity transportation

This study focuses on passengers undertaking pre-defined trips and establishes various transportation structure scenarios based on the characteristics of Beijing-Tianjin intercity transportation modes. The goal is to compute the carbon emissions for different transportation combinations and subsequently analyze the optimal travel modes. The schematic depiction of the study boundary is presented in Fig. 8. It should be noted that this study considers the intercity railroad trip between Beijing South Station and Tianjin Station, with a connecting distance of 5 km, resulting in a total distance of 140 km for the intercity high-speed travel mode.

This study explores three distinct intercity travel traffic scenarios, as depicted in Fig. 8, by optimizing the combination of short-distance and long-distance transportation options:

1) Scenario P1: The entire trip is completed using vehicles, and there are no interchanges.
2) Scenario P2: Intra-city transportation is carried out using vehicles, while intercity travel employs the railroad mode with two interchanges.
3) Scenario P3: Buses are used for intra-city transportation, and intercity travel involves using the railroad mode with two interchanges.

3.3.2. Scenarios for projecting carbon emission intensity

This analysis focuses on predicting carbon emissions for intercity transportation between Beijing and Tianjin, considering two key aspects and involving four influential factors. These factors include

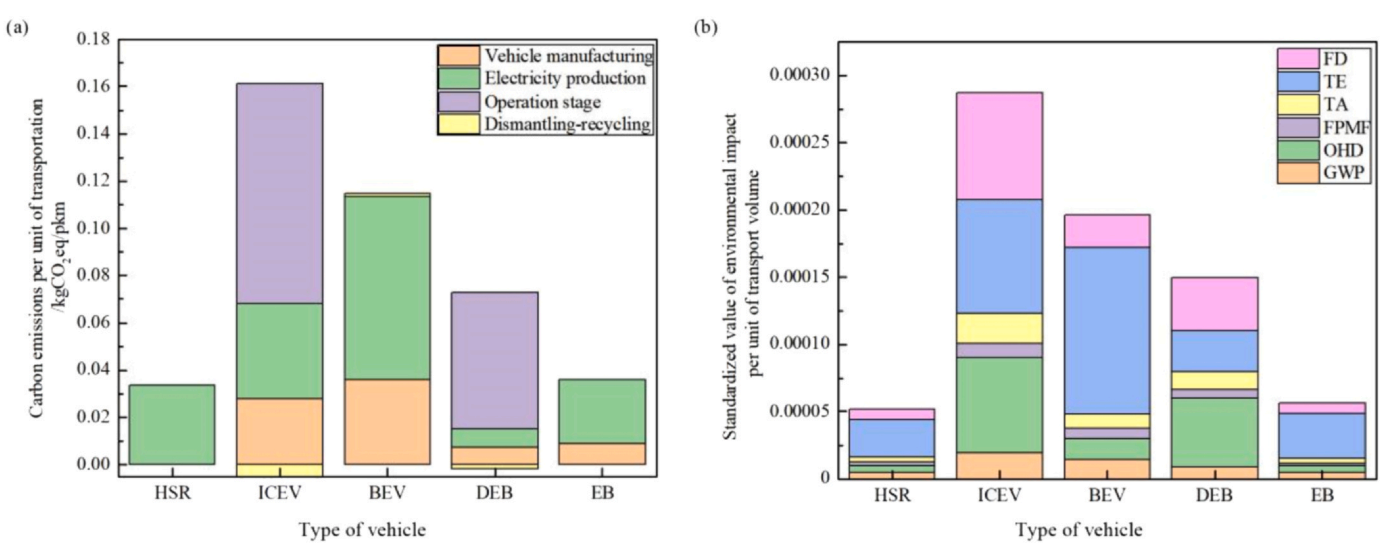

Fig. 7. The carbon emission and environmental impact for unit traffic volume. (a) The carbon emission of unit traffic volume; (b) The environmental impact of unit traffic volume.

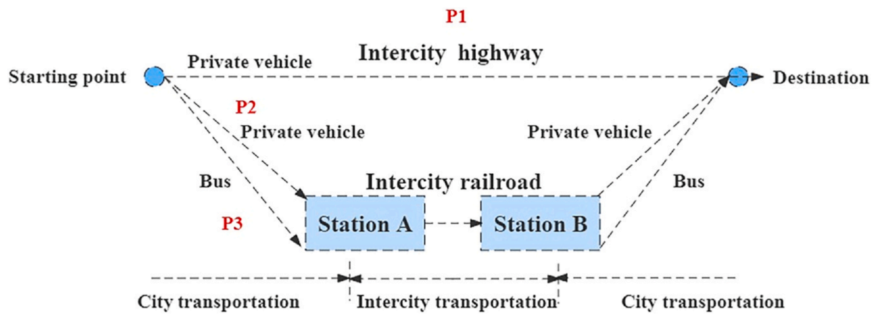

Fig. 8. Intercity Transportation Interchange Route Map.

Table 5
Illustrate of scenario setting.

Number	Name	Illustrate
S1	Baseline scenario	Using various indicators in 2020 as benchmark values, considering urban transportation carbon emissions trends based on the current policy measures and technological level
S2	Policy development scenario	Further optimization of energy structure, improvement of fuel efficiency and lightweight technology, increase in the ownership rate of new energy vehicles and new energy buses
S3	Enhanced emission reduction scenario	Source structure optimization, fuel efficiency improvement, and lightweight technological leapfrog progress, new energy vehicle ownership rate and new energy bus ownership rate of 100 %

technological advancements like optimizing energy structures and improving fuel efficiency, as well as policy-driven factors such as promoting higher adoption rates of new energy vehicles and increasing ownership of new energy buses. Based on these factors, three distinct scenarios have been formulated: a baseline scenario, a policy development scenario, and an enhanced emission reduction scenario. These scenarios and their key characteristics are summarized in Table 5.

3.3.3. Analysis of reduction potential for optimization of traffic structure

Fig. 9(a) shows the analysis of one-way carbon emissions within the Beijing-Tianjin intercity transportation scenarios under the baseline conditions. The results reveal that in 2020, the carbon emissions for the P1 scenario amount to 20.46 $kgCO_2eq$. In contrast, the P3 travel scenario represents only 24 % of the emissions recorded in the P1 scenario, and the P2 travel scenario is even lower at 28 % of the P1 scenario. By 2040, the carbon emissions in the P3 travel scenario are 22 % of the P1 scenario, while the P2 travel scenario reaches 27 % of the P1 scenario. As energy optimization progresses, this ratio declines further. In 2060, the one-way carbon emissions for the P3 travel scenario drop to merely 18 % of those observed in the P1 scenario trips. These findings underscore the substantial potential of HSR travel in effecting emission reduction in comparison to private vehicle travel.

The projected one-way transportation carbon emissions for the optimal scenario P3 are examined across various scenarios. Specifically, within the context of a more stringent emission reduction scenario, the one-way carbon emissions stand at 3580 $kgCO_2eq$, 1.71 kgCO2eq, and 1.24 $kgCO_2eq$ in 2030, 2050, and 2060, respectively. This represents reductions of 11 %, 23 %, and 28 % compared to the baseline projections, as illustrated in Fig. 9(b).

The transition between different travel modes will significantly affects the carbon emissions associated with Beijing-Tianjin intercity transportation. While the establishment of intercity rail systems will

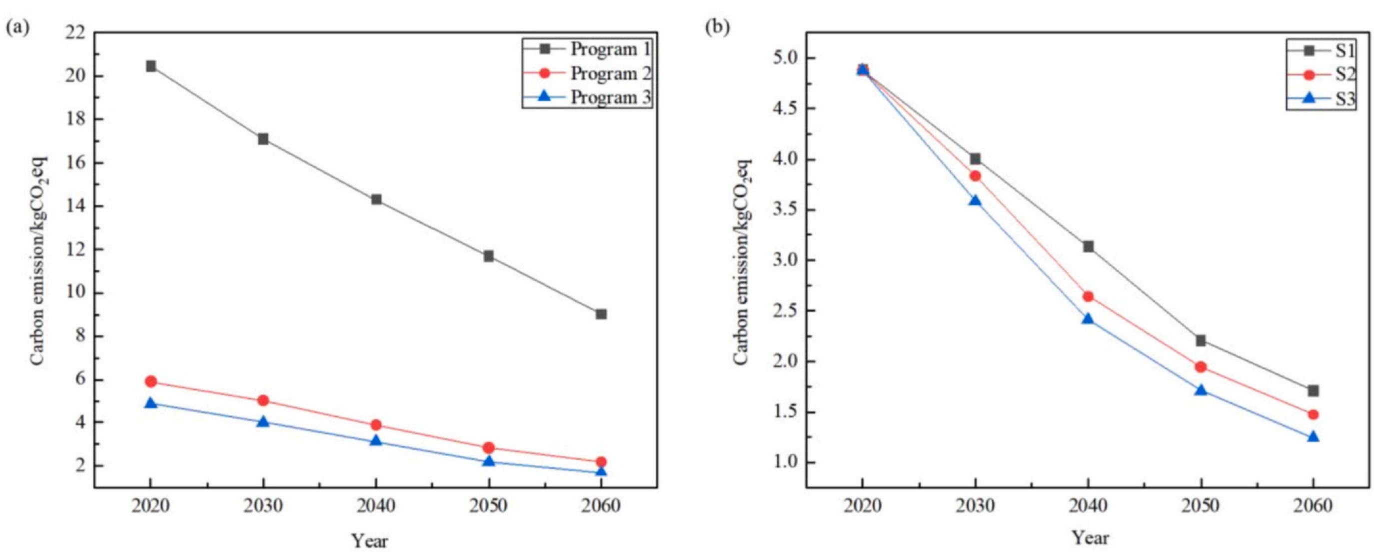

Fig. 9. Carbon emission of one-way transportation. (a) Carbon emission of one-way transportation for three programs in S1; (b) Carbon emission of one-way transportation for three scenarios in P3.

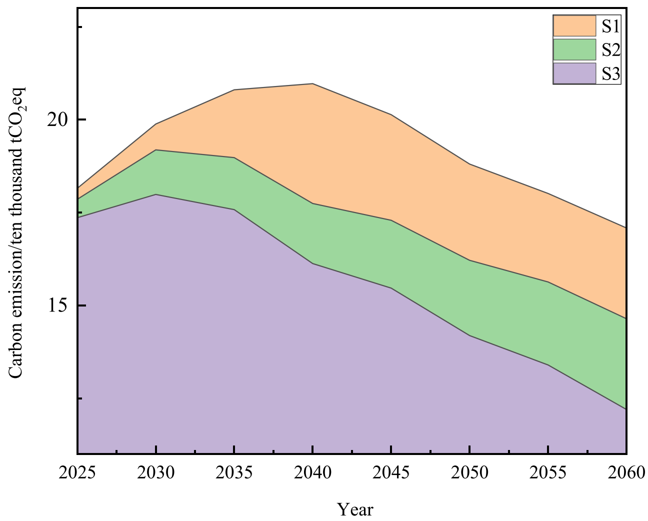

Fig. 10. Carbon emission of Beijing-Tianjin intercity transportation in three scenarios.

facilitate intercity commuting, the adoption of high-speed rail for cross-city journeys remains relatively modest. In the present phase, it remains imperative to prioritize the robust development of urban public transportation networks and the expansion of intercity rail infrastructure. This ongoing effort is essential for enhancing transportation structures, curbing energy consumption, and advocating for environmentally friendly modes of travel.

Railroad transportation demonstrates a significant edge in emission reduction when contrasted with road transportation for intercity travel. In this context, this section of the study aims to project the timing of peak carbon emissions for Beijing-Tianjin intercity railroad. This prediction is achieved by fitting the evolving pattern of passenger traffic volume within the Beijing-Tianjin intercity transportation system, coupled with an assessment of the alterations in carbon emission intensity per unit of high-speed rail operation under each scenario. The resultant insights aim to provide a solid foundation and guidance for the informed and reasonable formulation of emission reduction policies.

In the baseline scenario, the peak for carbon emissions in the Beijing-Tianjin intercity high-speed rail is estimated to occur around 2040, reaching a peak of 209600 tCO_2. Conversely, under both the policy development and deepening emission reduction scenarios, the anticipated peak is projected to transpire approximately in 2030, with respective peak values of 191800 tCO_2 and 179800 tCO_2 (Fig. 10). Notably, owing to the more profound optimization of the energy structure, the deepening emission reduction scenario showcases a 12 % and 8 % reduction in carbon emissions in 2030 compared to the baseline and policy development scenarios. Similarly, in 2060, the deepening emission reduction scenario demonstrates a 17 % and 29 % decrease in carbon emissions relative to the baseline and policy development scenarios. Consequently, adhering to the parameterization of the deepening emission reduction scenario (S3), a concerted effort to propel the adoption of clean energy sources is crucial to further curbing the consumption of fossil fuels.

4. Conclusion

The comprehensive carbon emissions resulting from the entire lifecycle of HSR trains amount to 4.18×10^9 $kgCO_2eq$, with the dominant share emanating from the operational phase of the vehicle. When considering the carbon emissions arising from fuel production and operational processes, it becomes evident that they constitute 81 %, 70 %, 82 %, 68 %, and 99 % of the total emissions for ICEV, BEV, DEB, EB and HSR, respectively. Notably, the adoption of electric energy as the propelling source for transportation yields a significant reduction in carbon emissions during the operation phase. Specifically, BEV and EB manifest a reduction of 27 % and 48 %, respectively, in comparison to ICEV and DEB.

The carbon emission intensity per unit and the standardized environmental impact value per unit for HSR stands at merely 24 %–32 % in comparison to vehicles, and 46 %–89 % when compared to buses, marking a substantial reduction in both cases. This significant reduction in emission intensity for HSR, compared to other modes of transportation, underscores its environmental superiority. In the context of one-way intercity transportation between Beijing and Tianjin, opting for HSR travel can lead to a remarkable reduction of carbon emissions by approximately 72 %–76 % in contrast to road travel. This solidifies HSR's position as a mode of transportation with a notable and effective emissions reduction impact, particularly when contrasted with private vehicle usage.

In the context of passenger transportation via the Beijing-Tianjin Intercity HSR, carbon emissions are predicted to reach their peak in 2040 under the baseline scenario. However, considering the Policy Development Scenario and the Deepening Emission Reduction Scenario, carbon emissions will hit their peak around 2030. Notably, the peak carbon emissions projected in the deepened emission reduction scenario are notably lower than those of the baseline scenario and policy development scenario, with reductions of 15 % and 4 % respectively. This emphasizes that a deeper optimization of the energy structure has the potential to significantly curtail carbon emissions from the Beijing-Tianjin intercity railroad transport, and can contribute to accelerating the occurrence of the peak carbon emissions from high-speed railway transportation.

Acknowledgements

The authors acknowledge the financial support of the National Natural Science Foundation of China (U2268208) and Science and Technology Program of China National Railway Group Co., Ltd. (N2022×037).

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