Report No. CSS13-26
December 13, 2013

Life Cycle Assessment of China's High Speed Rail Systems

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SUSTAINABLE SYSTEMS
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A project submitted in partial fulfillment of requirements
for the degree of Master of Science
(Natural Resources and Environment)

University of Michigan
Ann Arbor

December 13, 2013

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A report of the Center for Sustainable Systems
Report No. CSS13-26

Document Description

LIFE CYCLE ASSESSMENT OF CHINA'S HIGH SPEED RAIL SYSTEMS
Ye Yue
Center for Sustainable Systems, Report No. CSS13-26
University of Michigan, Ann Arbor, Michigan
December 13, 2013
18 pp., 7 tables, 10 figures, 1 appendix

This document is available online at: http://css.snre.umich.edu

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Abstract

China has built the world's longest network of High Speed Rail (HSR) systems in less than 5 years. However, there are very few studies on the life cycle impact of China's HSR systems compared to studies around the world. Environmental impacts of China's HSR could be very significant due to dependence on dirty coal-fired power and material and energy intensive bridges. Thus, a life cycle assessment of China's HSR systems is necessary.

Life Cycle Assessment (LCA) is used to investigate environmental impacts of China's HSR system between Beijing and Shanghai, assessing life cycle stages including: (1) vehicle manufacture, maintenance, and disposal; (2) infrastructure construction; (3) operation. Data from Chinese Ministry of Railway, Ecoinvent database, and Chinese Core Life Cycle Database (CLCD), are compiled to build the HSR's life cycle inventory. LCA software eBalance is used to conduct the analysis. Additional scenarios are developed by varying infrastructure composition, electricity mix, HSR development, travel length of cross-line vehicles, vehicle utilization, occupancy rate, and use of fly ash in concrete, in order to help identify major drivers of environmental impact and propose recommendations for improvement.

It is discovered that operation stage contributes to 72-91% of the impacts in Acidification Potential (AP), Primary Energy Demand (PED), Eutrophication Potential (EP), Global Warming Potential (GWP), and Respiratory Inorganics (RI). Vehicle stage contributes to 43% of impact in Chinese Abiotic Depletion Potential (CADP). Infrastructure construction accounts for 54% of impact in Chemical Oxygen Demand (COD) and 38% of impact in CADP. Scenario analysis identified several key drivers of impact, including proportion of bridge, tunnel, and reinforced subgrade, electricity mix, various factors that lead to different demands of HSR vehicle and transportation, and fly ash use in concrete. Several suggestions are proposed to improve life cycle environmental performance of HSR projects. It is also discovered that China's HSR systems have higher impact in RI than Germany's HSR and conventional rail systems, and lower impact in RI than Switzerland's road and air systems.

Acknowledgments

This research was generously supported and carefully guided by many individuals and organizations.

I would like to thank Professor Tao Wang from Ritsumeikan University in Japan for guiding the research through and providing very important data in infrastructure stage!

Thank Professor Jun Zhou from Central University of Finance and Economics in China for collecting data of infrastructure from Chinese Ministry of Railway!

Thank Ms. Jie Yang from Sichuan University in China for supporting this research and conducting analysis by eBalance and CLCD!

Thank Professor Hongtao Wang from Sichuan University in China for supporting this research and providing access to eBalance and CLCD!

Thank Professor Ming Xu, my committee chair, and Professor Greg Keoleian, my committee member, both from School of Natural Resources and Environment at University of Michigan, for advising me in this research and providing very helpful suggestions in both content and format!

Thank Professor Ming Xu for allowing me to continue conducting my research project for him about LCA of HSR systems as my master's thesis!

Thank Mrs. Helaine Hunscher from Center for Sustainable Systems at University of Michigan for kindly helping me revise and polish my thesis!

Thank Center for Sustainable Systems from School of Natural Resources and Environment at University of Michigan for supporting the research and providing access to SimaPro software!

This research was supported by National Natural Science Foundation of China, and Environment Research and Technology Development Fund (S-6-4) of the Ministry of the Environment, Japan.

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1 Introduction

As part of its aggressive plans for rail network, economic modernization and development, China has built the world's longest and most comprehensive network of High Speed Rail (HSR) systems in less than 5 years (Lu, 2012). The flagship among them is the world's second longest HSR project between Beijing and Shanghai with about 36 billion dollar investment (Li, 2007). Although China's HSR systems have the potential to save energy and cut greenhouse gas (GHG) emissions in operation compared with conventional transportation modes such as automobile and airplane, they also can have significant environmental impacts across their life cycles.

There have been several comprehensive life cycle assessment (LCA) studies on HSR systems mainly in the United States and Europe. In the United States, Chester and Horvath (2010) analyzed the life cycle (except for maintenance, disposal and supply chain) environmental performance of proposed California High Speed Railway (CAHSR) in comparison with alternative transportation modes in scenarios of high and low occupancies of ridership. It was discovered that CAHSR had lower GHG emissions and end-use energy consumption at high occupancy, and higher SO_2 emissions at low occupancy as it is mainly powered by fossil-based electricity. CO, NO_X, VOC, and PM_{10} emissions mostly came from infrastructure construction rather than emissions from vehicle operation. Chang and Kendall (2011) followed their study by a process-based LCA study on GHG emissions estimation in the construction of CAHSR infrastructure with specification of several infrastructure types depending on terrains. They found that 80% of the infrastructure emissions were from material production, and tunneling and aerial structures which took only 15% of the route's length but contributed 60% of the emissions.

In Europe, Åkerman (2010) used simplified LCA to research the mitigating climate change effect of a proposed Swedish high-speed rail track and found significant reduction of GHG emissions due to transportation modes shifting to HSR, though new railway construction and maintenance may weaken that effect. von Rozycki et al. (2003) carried out a screening LCA study (called *ecology profile*) of a major German HSR and discovered the dominant share of traction in energy consumption, the major role of railroad infrastructure in resource consumption and significant energy-consuming activities such as construction of tunnels and rail points heating during winter.

Other supporting studies including the Life Cycle Inventories (LCI) for energy, GHG and criteria air pollutant emissions of diverse passenger transportation modes in the United States including CAHSR by Chester (2008), the environmental rebound effects (ERE) of a proposed Swiss HSR system by Spielmann et al. (2008), and LCA studies by Lee et al. (2008), Miyauchi et al. (1999) and Ueda et al. (1999) on individual components of HSR systems including infrastructures, vehicles and materials, respectively.

Besides LCA studies on HSR systems, other approaches have been applied to investigate the environmental impacts of HSR systems. Levinson et al. (1997) evaluated the social costs of the HSR systems between Los Angeles and San Francisco including traditional environmental impacts such as air pollution and noise pollution. Taylor et al. (1997) presented

a brief, conclusive description of the 1996 California "High Speed Rail Corridor Evaluation & Environmental Constraints Analysis" that assessed natural environment impacts, social and cultural resources impacts, land-use impacts, and engineering or environmental constraints of three corridors. Wee et al. (2003) utilized cost-benefit analysis to investigate mainly the environmental impacts of the Zuider Zee line, a proposed rail link to run between the west and the north of Netherlands. Coutinho et al. (2005) presented a methodology called Strategic Environmental Assessment (SEA) to assess Portugal's high speed train network.

Some researchers compared HSR with other transportation modes by non-LCA approaches and some of them discovered the environmental benefits of HSR. Wayson and Bowlby (1989) compared noise and air pollutant emissions of several European and Asian HSR systems with conventional rail and air transport, and concluded that HSR has environmental benefits over other conventional intercity mass-transportation systems. Janic (2003) compared environmental performances between European HSR and air passenger transport, and discovered that transition from air passenger transport to HSR could mitigate the environmental impacts. Givoni (2006) reviewed the overall development and impact of the modern HSR systems, and concluded that HSR resulted in less environmental impact than aircraft and car, though the environmental benefits of HSR infrastructure and services remain unclear. Later, Givoni (2007) compared the environmental impact of a flight and a HSR trip between London and Paris in terms of local air pollution and climate change impacts, and discovered that the substitution of an aircraft seat by an HSR seat could lower the environmental impact. However, Federici et al. (2008) used material flow accounting, embodied energy analysis, exergy analysis and emergy synthesis to compare several terrestrial transport systems such as highways, railways and HSR systems, and HSR was found to be not energy-saving compared with automobiles due to energy intensive infrastructure construction processes.

As HSR is developed based on conventional rail systems, LCA of conventional rail systems compared with other transportation modes can be to some extent helpful in understanding the environmental impact of HSR. In a series of hybrid LCA studies, it was found that U.S. conventional rail systems have relatively low energy consumption, greenhouse gas emissions, and air pollutant emissions (including CO_2, NO_x, PM_{10}, CO, and SO_2) compared to air and road freight systems, but relatively high SO_2 emissions in passenger transportation due to coal-fired power for vehicle operation and removal of sulfur from gasoline and diesel fuels (Chester and Horvath, 2009; Facanha and Horvath, 2007; Facanha and Horvath, 2006). Spielmann and Scholz (2005) conducted a life cycle inventory analysis of freight transport systems and found that rail systems have the lowest environmental impacts compared to barge and lorry systems, except for PM_{10} due to abrasion processes. Spielmann et al. (2005) carried out an attributional prospective LCA and found that rail is the best alternative for Swiss future regional transport in terms of environmental impacts.

Although China's HSR systems have become the longest in the world, there has not been a comprehensive life cycle assessment study of China's HSR systems to evaluate its environmental impacts. Rather than life cycle environmental impact, environmental benefits or impacts including energy-saving, reducing oil dependence, and conventional

environmental impacts including noise, water pollution, air pollution, solid wastes, and ecological damage in construction are emphasized (Peng, 2013; Wang, 2013; Zhou, 2012). As China's HSR systems highly depend on bridges to cross diverse terrains, which require considerable amount of material and energy to construct, and rely on electricity mix largely from coal-fired power plants, China's HSR systems may potentially have very significant life-cycle environment impact compared to other HSR systems and transportation modes. Thus, a life cycle assessment of China's HSR systems is necessary to assess its environmental impact, and to serve as guidance for future HSR projects to reduce their life-cycle environmental impact. Therefore, the 1318-km long HSR system between Beijing and Shanghai is selected to be researched through a life cycle assessment method, as it is the world's second longest HSR system and also the flagship HSR system in China.

2 Methodology

2.1 Life Cycle Assessment Method and Data Sources

To assess the life cycle environmental impacts of China's HSR system between Beijing and Shanghai, its life cycle is divided into three stages: (1) vehicle manufacture, maintenance, and disposal; (2) infrastructure construction; (3) operation. Due to the fact that China's HSR systems are just built in recent years and there is limited data about operation, maintenance and disposal of infrastructure, these stages are not considered in this research. The system boundary also excludes facilities used for each life cycle stage and for material, energy and equipment transportation due to lack of data. The function of the analyzed system is to transport passengers between Beijing and Shanghai. The functional unit is per seat per kilometer traveled (skm). In the scenario analysis considering occupancy rate, the functional unit is converted into per passenger per kilometer traveled (pkm).

Due to lack of life cycle inventory data for China's HSR vehicle, life cycle inventory data of Germany's Inter-City Express (ICE) HSR vehicle from the Ecoinvent database are converted to represent the data for China's HSR vehicle, as China's HSR vehicle CRH3 was developed using Germany's ICE-3, or Siemens's Velaro as a prototype (Li et al. 2011). The conversion factor is calculated mainly based on the relationship of weight and number of vehicle carriages between China's HSR and Germany's ICE HSR. The life cycle inventory data for infrastructure construction are from Chinese Ministry of Railway. The data for operation are also from the ICE HSR in Ecoinvent database, while the electricity mix is replaced by China's electricity mix.

In the baseline scenario, according to the data from Chinese Ministry of Railway, for simplicity it was assumed that average travel distance of cross line vehicles is 900 kilometers (L); average occupancy rate is 70% (OR); total seats per vehicle with 16 carriages is 1000 (S); vehicle utilization is twice per day (U); there are 135 vehicles needed (V) to fulfill the demand in this scenario of mid-term HSR development stage determined by a moderate level of parameters including HSR trips and travel length per year per capita, and proportions of HSR travel in this line among total HSR passenger transport. Therefore by calculation, there

are 1.314E+10 skm for each vehicle in its 20-year lifetime (Y), assuming 365 days a year. Considering the amount of vehicles, there are 8.863E+12 skm for the whole project in the 100-year life time (Y) of the infrastructure. Equation (1) and (2) below are used to calculate the amount of material and energy consumption allocated to every seat kilometer traveled (q) in each stage in the baseline scenario.

$$q_{vehicle} = Q_{vehicle} / (S \times L \times U \times 365 \times Y_{vehicle}) = Q_{vehicle} / 1.314E+10 \text{ skm} \quad (1)$$

$$q_{infrastructure} = Q_{infrastructure} / (S \times L \times U \times 365 \times V \times Y_{infrastructure}) = Q_{infrastructure} / 8.863E+12 \text{ skm} \quad (2)$$

In these equations, Q is the amount of material or energy consumption in each stage in the given lifetime of vehicle or infrastructure, with the unit kg or J. For other infrastructure components, the total skm will change according to their lifetime, thus leading to a change of material and energy consumption per seat per kilometer traveled. Regarding the operation stage, the data of electricity consumption per seat per kilometer traveled is directly available from the Ecoinvent database.

LCA software developed by IKE Environmental Technology Co. Ltd., eBalance, together with China's national background LCI database, Chinese Core Life Cycle Database (CLCD), are used to conduct the LCA of China's HSR system between Beijing and Shanghai, so as to ensure all life cycle inventory data can be analyzed under China's material and energy context. Seven categories of life cycle impacts, including Acidification Potential (AP, measured by kg SO_2 equivalent), Chinese Abiotic Depletion Potential (CADP, measured by kg coal resources equivalent), Primary Energy Demand (PED, measured by kg standard coal equivalent), Chemical Oxygen Demand (COD, measured by kg oxygen demanded), Eutrophication Potential (EP, measured by kg PO_4^{3-} equivalent), Global Warming Potential (GWP, measured by kg CO_2 equivalent), and Respiratory Inorganics (RI, measured by kg $PM_{2.5}$ equivalent), are investigated by using eBalance and CLCD. Default impact assessment and normalization methods in the eBalance software, including CML 2002, ISCP 2010, IPCC 2007, IMPACT 2002+, and normalization reference of China in 2010, are used in the impact assessment.

2.2 Scenario Analysis

After estimating the current life cycle environmental impact of China's HSR between Beijing and Shanghai as the baseline scenario, scenario analysis is conducted to evaluate variation of life cycle environmental impact in different situations with variations in infrastructure composition, electricity mix, HSR development, travel length of cross-line vehicle, vehicle utilization, occupancy rate, and use of fly ash in concrete.

With regard to infrastructure composition, seven additional scenarios are developed based on different proportion of bridges, tunnels, and reinforced subgrade. Regarding electricity mix, eight additional scenarios are developed based on different proportions of coal-fired power, hydropower, nuclear power, and wind power. In terms of HSR development stage, which represents the different levels of technology maturity and adoption of the HSR systems nationwide, two additional scenarios about short-term and long-term development of HSR systems are created based on different demands for HSR travel in different development stages, while the baseline scenario is considered as mid-term scenario. For each category of

scenarios including travel length of all cross-line vehicles that utilize the HSR infrastructure between Beijing and Shanghai, and vehicle utilization which represents average daily utilization rate of each vehicle, two additional scenarios are developed based on low and high level of travel length of cross-line vehicles and vehicle utilization. With regard to scenarios about occupancy rate, two additional scenarios are developed based on low and high level of occupancy rate, and all scenarios including the baseline use pkm instead of skm as the functional unit. Regarding use of fly ash in concrete, one additional scenario is developed based on elimination of fly ash use in concrete. By looking into variation of environmental impacts in different scenarios, major drivers of environmental impact can be identified to help propose recommendations to improve environmental performance of HSR systems. Table 1 shows the five categories of scenarios and their settings.

Table 1. Scenario categories and settings

Scenario Categories	**Scenario Settings**
Infrastructure composition	For scenario 1 to 3, proportions of bridges are lowered from 80.4% in baseline to 70%, 60%, and 50%; for scenario 4 to 5, proportions of tunnels are increased from 1.2% in baseline to 5% and 10%; for scenario 6 to 7, proportions of reinforced subgrade are increased from 18% in baseline to 40% and 60%; proportions of subgrade are changed as per the settings above to keep the total distance of 1318 km unchanged. Changes in these infrastructure components are based on their proportions in baseline so that there are no abrupt or extreme changes.
Electricity mix	For scenario 1 to 2, proportions of hydropower are increased from 15% in baseline to 20% and 25%; for scenario 3 to 5, proportions of nuclear power are increased from 2% in baseline to 7% and 12%; for scenario 6 to 8, proportions of wind power are increased from 2% in baseline to 7%, 12%, and 15%; proportions of coal-fired power are changed from 81% in correspondence to the settings above to keep the total electricity mix at 100%. Changes of these energy sources are based on their proportions in baseline and the possibility of major changes.
Development stage, travel length of cross-line vehicle, and vehicle utilization	For scenario 1 to 2, the development stage of HSR is changed from mid-term in baseline which needs 135 vehicles, to short-term and long-term by changing the HSR trips and travel length per year per capita, and proportions of HSR travel in this line among total HSR passenger transport, leading to 63 and 225 vehicles needed; for scenario 3 to 4, average travel distance of cross-line vehicles is changed from 900 km in baseline to 500 km and 1318 km, leading to 243 and 92 vehicles needed; for scenario 5 to 6, vehicle utilization is changed from two trips per day in baseline to one trips and trips travels per day, leading to 270 and 90 vehicles needed.
Occupancy rate	For scenario 1 to 2, occupancy rate is changed from 70% in baseline which needs 135 vehicles to 40% and 100%, leading to 236 and 94 vehicles needed.

Fly ash use in concrete	In scenario 1, all fly ash used in concrete in the baseline is replaced by the same amount of cement.

3 Results

3.1 Life Cycle Assessment Results

As shown in Figure 1, for AP, PED, EP, GWP, and RI, the operation stage contributes to 72%-91% of the life cycle environmental impact. This is because operation of the HSR system consumes a large amount of electricity mainly from coal-fired power plants, which emit considerable amount of SO_2, NO_x, CO_2, $PM_{2.5}$, and burn significant amount of coal. With regard to CADP, HSR vehicle and infrastructure use significant amounts of copper, which has the largest impact on CADP compared to other major materials including steel, concrete, and aluminum. This leads to the dominant contribution to this impact category by HSR vehicle and infrastructure compared to operation. Regarding COD, as use of concrete, steel, and copper in infrastructure construction all contribute significantly to COD impact, infrastructure construction contributes to about half of impact in COD.

Figure 2 shows that in CADP impact category, copper contributes to 89% of the impact in vehicle stage, followed by aluminum at 5%. Copper also contributes to 62% of the impact in infrastructure stage, while steel contributes 35%. In vehicle, the use of aluminum is about twice the amount of copper, and the use of steel in vehicle is about ten times that of copper; regarding infrastructure, the use of steel is 200 times that of copper. However, as one kilogram of copper contributes to 1.12E+04 kilogram Coal-R eq., compared to 3.07E+01 for steel and 2.49E+02 for aluminum, the dominant impact is from copper. In COD impact category, steel contributes to 91% of the impact in infrastructure stage, followed by diesel taking only 5%. This is because infrastructure uses a large amount of steel which also has relatively high impact in COD per unit.

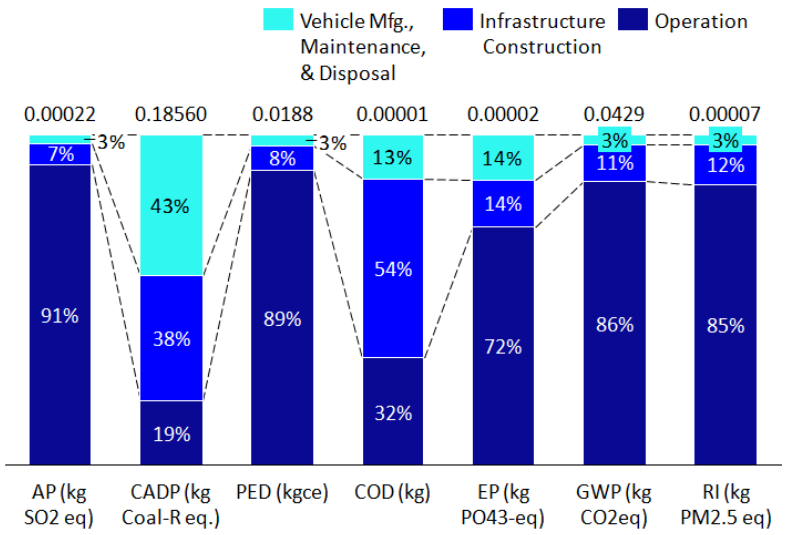

Figure 1. Life cycle impact of China's HSR system between Beijing and Shanghai

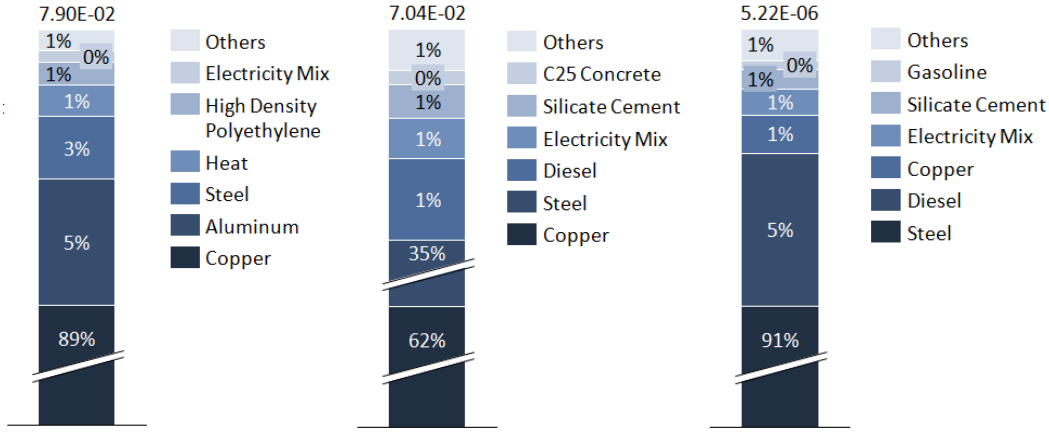

Figure 2. Sources of impact: CADP in vehicle stage and infrastructure stage, and COD in infrastructure stage, respectively

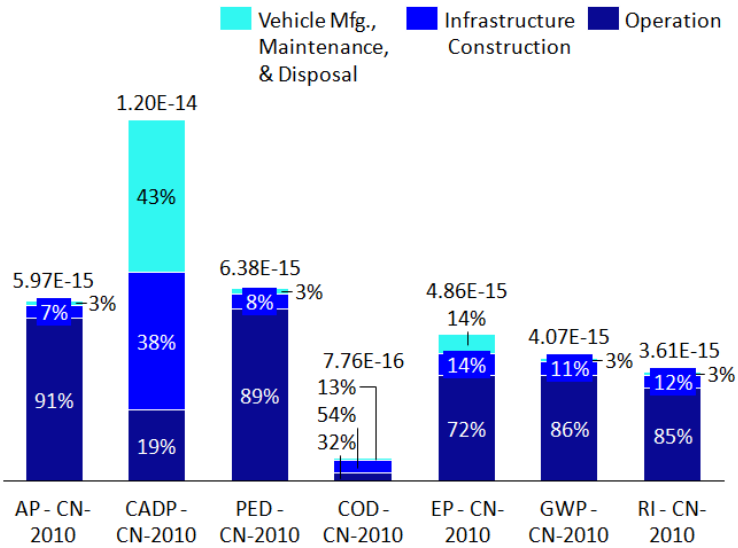

Figure 3. Normalized life cycle impact of China's HSR system between Beijing and Shanghai

After normalization of seven categories of life cycle impacts using the Chinese 2010 reference value for normalization in eBalance (IKE Environmental Technology Co. Ltd., 2012), it is shown in Figure 3 and Figure 4 that CADP contributed to 32% of the normalized life cycle impact, followed by PED (17%), AP (16%), EP (13%), GWP (11%), RI (10%), and COD (2%). Operation contributes to 63% of the overall life cycle impact due to its dominance in five impact categories, while infrastructure and vehicle lead to 20% and 17% of impact respectively, mainly due to dominance in CADP, the largest impact category among the seven.

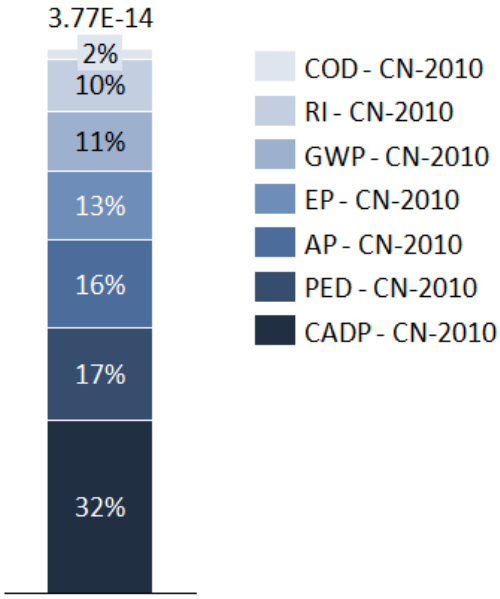

Figure 4. Proportion of normalized life cycle impact of China's HSR system between Beijing and Shanghai

3.2 Scenario Analysis Results

Figure 5 shows the variation of life cycle impact in each impact category under different scenarios of infrastructure composition. In scenario 1, 2, and 3, the proportions of bridge are reduced to 70%, 60%, and 50% from 80.4%, respectively, resulting in a significant decrease in COD, which means that bridges contribute significantly to the COD impact category. In scenario 4 and 5, the proportions of tunnel are increased to 5% and 10% from 1.2%, respectively, leading to a slight increase in COD, which means that tunnels contribute to COD impact as well, but less than bridges. In scenario 6 and 7, the proportions of reinforced subgrade are increased to 40% and 60% from 18%, respectively, leading to a small increase in COD, which means that reinforced subgrade contributes to COD impact as well, but also less than bridges. The proportion of changes to bridge, tunnel, and reinforced subgrade are compensated by decrease or increase of the same distance of ordinary subgrade, which has relatively lower impact compared to other types of infrastructure. After normalization of the impact variation, proportion variation of the bridge has the largest impact to COD and CADP, followed by reinforced subgrade and tunnel.

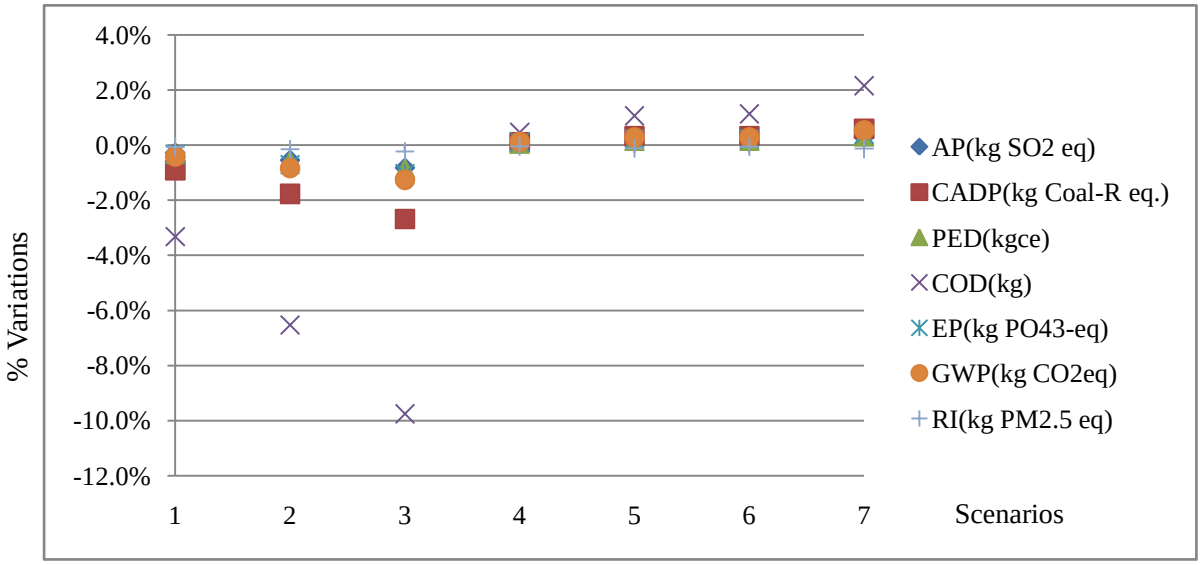

Figure 5. Life cycle impact variation of different scenarios of infrastructure composition

Figure 6 shows the variation of life cycle impact in each impact category under different scenarios of electricity mix. In scenario 1 and 2, the proportions of hydropower are increased from 15% to 20% and 25%, respectively, resulting in a significant decrease of GWP, RI, AP, PED, and EP, as hydropower does not emit much CO_2, NO_x, SO_x, and $PM_{2.5}$, and consumes less primary energy. In scenario 3, 4, and 5, the proportions of nuclear power are increased from 2% to 7%, 12%, and 17%, respectively, leading to a considerable decrease in GWP, RI, AP, and EP, and slightly more decrease in PED, as nuclear power has similar advantages compared to hydropower and uses less primary energy in its life cycle. In scenario 6, 7 and 8, the proportions of wind power are increased from 2% to 7%, 12%, and 17%, respectively, resulting in a significant decrease in GWP, RI, AP, PED, and EP similar to hydro power, as wind power has similar advantages compared with hydropower. However, wind power can lead to a very significant increase of impact in CADP, which is due to large use of metals and land. The proportion changes of hydropower, nuclear power, and wind power are compensated by a decrease of the same proportion of coal-fired power, which is viewed as a dirty energy source. Due to lack of data about solar power in CLCD, no scenario is developed to investigate the impact on environmental performance by using more solar power.

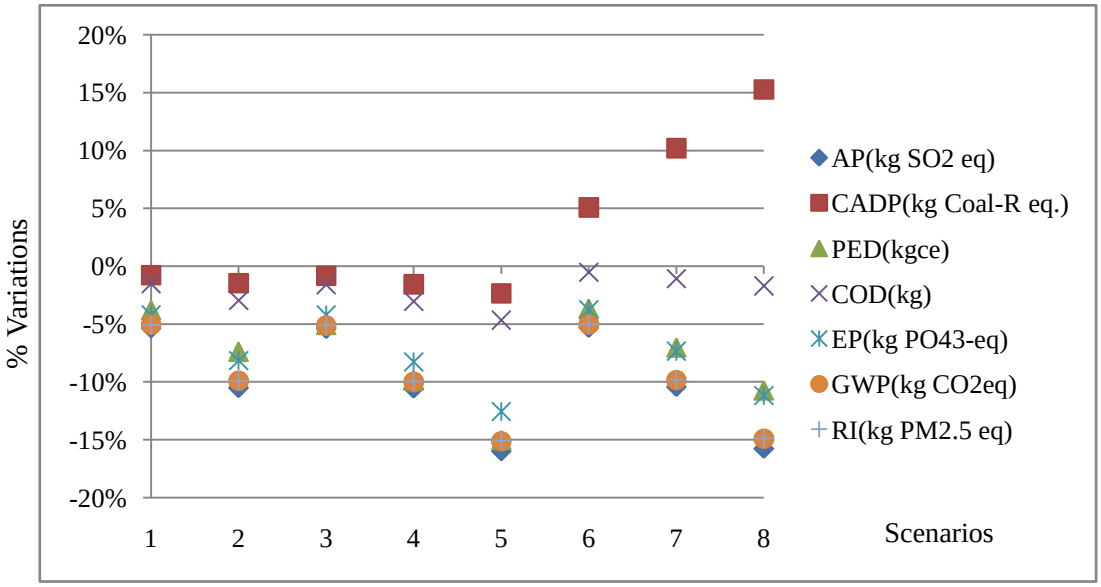

Figure 6. Life cycle impact variation of different scenarios of electricity mix

Figure 7 shows the variation of life cycle impact in each impact category under different scenarios of development stage, travel distance of cross-line vehicle, and vehicle utilization. In scenarios 1 about short-term development, parameters including HSR trips and travel length per year per capita are relatively lower, and proportions of HSR travel in this line among total HSR passenger transport is relatively higher than the baseline, leading to smaller amount of vehicle and total amount of skm for the whole project. This has led to the increase of impact categories including PED, AP, EP, GWP, and RI, especially COD and CADP due to fewer total skm allocated to the infrastructure. In scenario 2 about long-term development, the parameters are contrary to scenario 1, resulting in a larger amount of vehicle and total amount of skm for the whole project. This has led to the decrease of impact categories including PED, AP, EP, GWP, and RI, especially COD and CADP due to more total skm allocated to the infrastructure.

In scenario 3 and 5, as shorter cross-line travel distance and lower vehicle utilization all contribute to a smaller amount of total skm per vehicle, impacts highly influenced by vehicle stage including EP, COD, and especially CADP, are all increased compared to the baseline; while in scenario 4 and 6, as larger cross-line travel distance and higher vehicle utilization all lead to a larger amount of total skm per vehicle, impacts including EP, COD, and CADP are all reduced compared to the baseline. The asymmetric variations of impacts between different scenarios are due to the disproportional but realistic and linear variations of different sets of parameters.

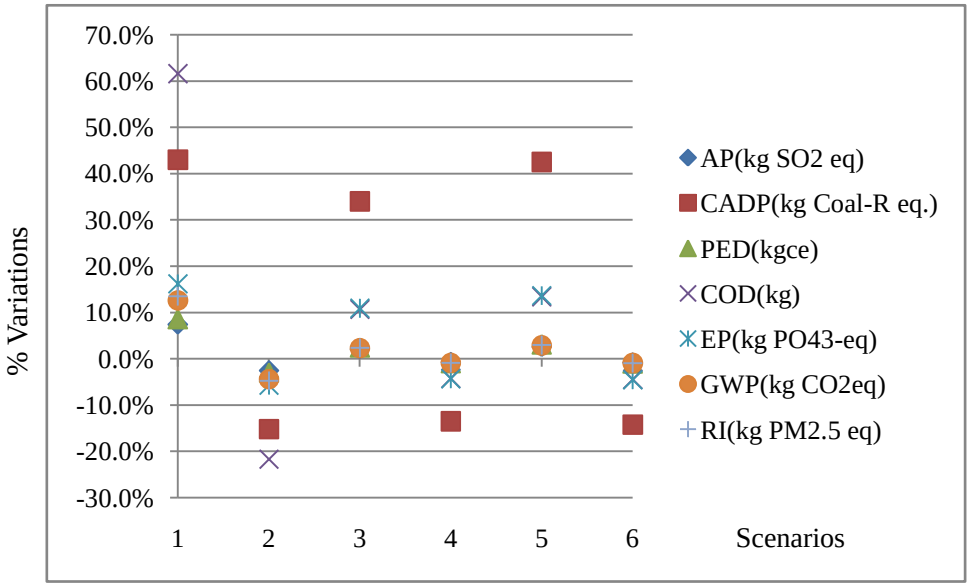

Figure 7. Life cycle impact variation of different scenarios of development stage, cross-line, and vehicle utilization

Figure 8 shows the variation of life cycle impact in each impact category under different scenarios of occupancy rate. In scenario 1 with 40% occupancy rate, a dramatic increase of electricity use on a functional unit basis and number of HSR vehicles needed to fulfill the same total pkm lead to an increase of all impact categories by 34%-70%, especially in PED, GWP, AP, EP, and AI, in which impact from operation dominates. In scenario 2 with 100% occupancy rate, decrease of electricity use on a functional unit basis and number of HSR vehicles needed to fulfill the same total pkm lead to a decrease of all impact categories by 19%-28%, especially in PED, GWP, AP, EP, and AI for the same reason.

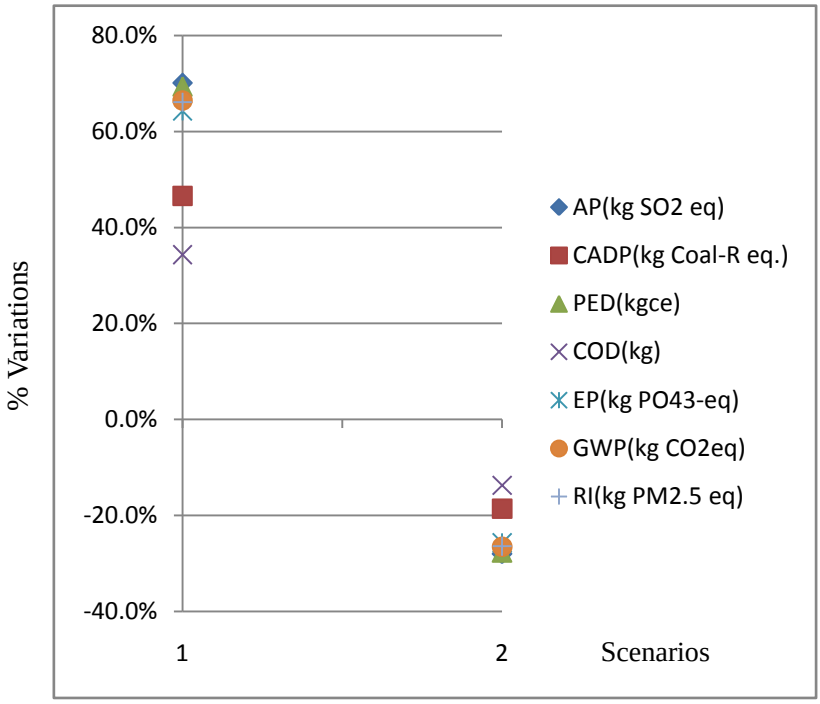

Figure 8. Life cycle impact variation of different scenarios of occupancy rate

Figure 9 shows the variation of life cycle impact in each impact category under the scenario of eliminating fly ash use in concrete. The elimination of fly ash is compensated by an increase in the same amount of cement. For the impact from infrastructure, the elimination of fly ash leads to over 5% increase of GWP, PED, and AP, due to the environmental impact from producing cement. For the overall project, the elimination of fly ash still leads to 1% increase of GWP, due to large use of cement in the infrastructure.

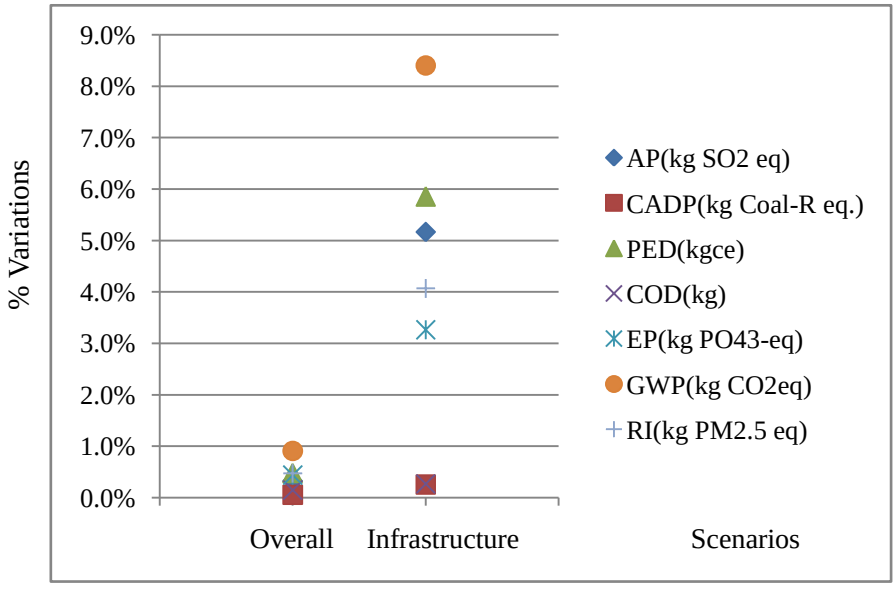

Figure 9. Life cycle impact variation of different scenarios of fly ash use in concrete

4 Discussion

4.1 Implication of Results and Suggested Improvements

According to the LCA results, the operation stage leads to major environmental impacts in AP, PED, EP, GWP, and RI, because of China's dirty electricity mix from coal-fired power plants that emit a huge amount of SO_2, NO_x, CO_2, and $PM_{2.5}$. Infrastructure construction contributes mostly to COD and CADP, mainly due to considerable consumption of steel in all types of infrastructure and copper use. Vehicle manufacturing, maintenance, and disposal stage contributes significantly to CADP, primarily due to substantial impact from use of copper in vehicle manufacturing.

To dig deeper by scenario analysis, bridges contribute significantly to COD impact primarily due to large use of steel in bridge infrastructure. Clean electricity sources all have a strong potential to decrease life cycle impact in operations by replacing coal-fired power. While hydropower, nuclear power, and wind power all have similar benefits in GWP, RI, and AP, wind power may bring additional environmental impact in CADP due to large use of metal and land, while nuclear power has slightly lower PED impact. Different development stages can lead to different impacts mainly in COD and CADP, and more mature development of HSR has lower environmental impact due to more skm allocated to infrastructure. Different travel distances of cross-line vehicle and vehicle utilization rates can lead to different impacts mainly in CADP and EP, and longer travel distance of cross-line vehicle and higher vehicle utilization are preferred due to larger skm per vehicle. Different occupancy rates can have different impacts in all impact categories, and higher occupancy rate can lead to lower impacts in CADP, COD, and especially PED, GWP, AP, RI, and EP mainly due to more efficient use of electricity and fewer vehicles needed. Use of fly ash in concrete can significantly decrease impact of GWP, PED, and AP mainly due to large use of cement in infrastructure.

According to the key findings above, to better improve the life cycle environmental performance of HSR systems, several approaches are recommended. First, current dirty electricity mix composed mainly of coal-fired power should be shifted to cleaner energy sources including nuclear power, wind power, hydropower, and likely solar power, in order to justify the possible environmental benefits of HSR operation. Second, various measures should be taken to reduce environmental impact from HSR vehicle, such as dematerialization of vehicle, better scheduling and utilization, boosting occupancy rate, increasing travel length of cross-line vehicle, and further develop HSR systems to achieve maturity. Third, if given appropriate geographic conditions, bridges, tunnels, and reinforced subgrade should be avoided as long as safety, speed, and land use are not sacrificed. Fourth, use of fly ash in concrete to reduce environmental impact, and other approaches to reuse and recycle low-value and low-impact resources to replace high-impact materials should also be developed and utilized to further reduce environmental impact from intensive material use.

4.2 Comparisons and Limitations

Due to limited data on other transportation modes in China from CLCD, quantitative comparison of life cycle impact with other transportation modes in China cannot be made directly in the scope of this study. However, comparison with ICE and other transportation modes in Europe can be made by using SimaPro software, and results of another LCA study on rail systems using the same software eBalance and impact assessment method can be included as a reference. As eBalance uses the same impact assessment method for RI compared with SimaPro, SimaPro is used to conduct an LCA of Germany's ICE and conventional rail systems and Switzerland's road and air transport systems to compare with China's HSR systems. For other types of impacts, since the two software tools use different assessment methods or have different types of impact categories, they are not directly comparable. Maintenance, operation, and disposal stage of infrastructure are excluded to keep the same scope with this research. Meanwhile, the result of a recent LCA study of railway freight transportation using eBalance and CLCD by Yang et al. (2013) is used in the comparison only as a reference, although this study does not consider vehicle manufacturing, maintenance, and disposal stage. The functional unit for China's railway freight transportation is ton per kilometer traveled, making direct comparison infeasible; while for others the functional unit is passenger kilometer traveled assuming 100% occupancy rate so that the unit can be converted directly to seat kilometer traveled.

In Figure 10, the impact category RI has the same impact assessment method in both eBalance and SimaPro, so this figure is the most valid for comparison among different transportation modes. Figure 10 shows that China's HSR systems' impact in respiratory inorganics (CN HSR-RI) is higher than Germany's ICE (DE HSR-RI) and rail systems (DE Rail-RI), but lower than Switzerland's road (CH Road-RI) and air systems (CH Air-RI). As the respiratory inorganics impact is caused by electricity use in operation and operation stage contributes heavily to most categories of environmental impact, it is very likely that the impact order in this figure may be close to the result for other impacts. Thus, China's HSR systems may have larger environmental impacts than Germany's ICE and rail systems in most other impact categories, mainly due to the dirty electricity mix mostly relying on coal-fired power.

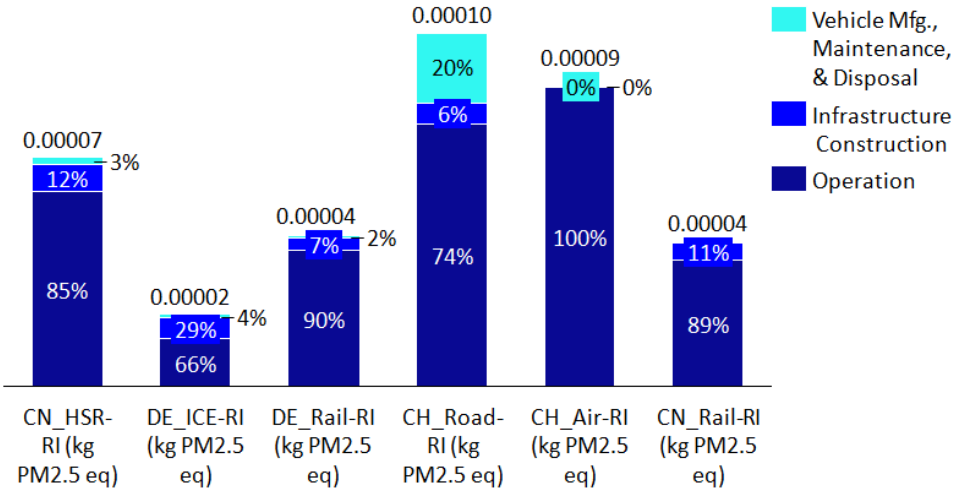

Figure 10. Respiratory Inorganics of China's HSR systems, Germany's ICE and rail systems, Switzerland's road and air systems, and China's rail systems (for freight transportation)

Although this research has been the first to conduct an LCA of China's HSR between Beijing and Shanghai using China specific database and software, availability of data has limited the accuracy of the results. Meanwhile, CLCD and eBalance are still being developed and more useful data and processes including those of solar power will be added, meaning the future results can be made more comprehensive and accurate. Moreover, due to lack of life cycle inventory data in other transportation modes in China, comparison among all available transportation modes cannot be directly conducted, which has limited the benefit of this research.

5 Conclusions

By using China-specific LCA software and databases, this research has assessed the life cycle impact of China's HSR system between Beijing and Shanghai from its major life cycle stages. It was found that the operation stage contributes significantly to AP, PED, EP, GWP, and RI, while infrastructure and HSR vehicle contribute to considerable impact in CADP and COD, respectively. Through scenario analysis, it is found that by reducing the proportion of coal-fired power, bridge and tunnel, optimization of the system to better utilize every HSR vehicle, and using fly ash, substantial life cycle environmental impact can be reduced. This study is compared with other LCA research on railway transport and results from SimaPro software. Although this study has many limitations due to lack of life cycle inventory data, it plays a pioneering role to inspire and support future research on life cycle impact of China's HSR systems and comparable transportation modes.

Appendix

Table 2. Scenario settings for infrastructure composition

Scenarios	Bridge	Tunnel	Reinforced Subgrade	Subgrade
Baseline	1059.4（80.4%）	16.1（1.2%）	83.9 (6.4%)	379
Scenario 1	922.6（70%）	16.1（1.2%）	83.9 (6.4%)	515.8
Scenario 2	790.8（60%）	16.1（1.2%）	83.9 (6.4%)	647.6
Scenario 3	659（50%）	16.1（1.2%）	83.9 (6.4%)	779.4
Scenario 4	1059.4（80.4%）	65.9（5%）	83.9 (6.4%)	329.2
Scenario 5	1059.4（80.4%）	131.8（10%）	83.9 (6.4%)	263.3
Scenario 6	1059.4（80.4%）	16.1（1.2%）	185.2 (14%)	277.7
Scenario 7	1059.4（80.4%）	16.1（1.2%）	277.7 (21%)	185.2

Note: the proportion is based on 1318-km total length of the project for simplicity, as there are overlaps of infrastructure that lead to a total infrastructure length of longer than 1318 km.

Table 3. Scenario settings for electricity mix

Scenarios	Coal-Fired Power	Hydro Power	Nuclear Power	Wind Power
Baseline	81%	15%	2%	2%
Scenario 1	76%	20%	2%	2%
Scenario 2	71%	25%	2%	2%
Scenario 3	76%	15%	7%	2%
Scenario 4	71%	15%	12%	2%
Scenario 5	66%	15%	17%	2%
Scenario 6	76%	15%	2%	7%
Scenario 7	71%	15%	2%	12%
Scenario 8	66%	15%	2%	17%

Note: solar power is not included due to lack of relevant data and processes in CLCD.

Table 4. Scenario settings for HSR development stage, travel length of cross-line vehicle, and vehicle utilization

Scenarios		Number of Vehicle Needed	Scenario Setting
Baseline		135	Medium term development, 900 km cross-line length, 2 travel/day/vehicle
HSR Development Stage	Scenario 1	63	Short-term development (low total skm)
	Scenario 2	225	Long-term development (high total skm)
Cross-Line Vehicle	Scenario 3	243	500 km cross-line (low skm/vehicle)
	Scenario 4	92	1300 km cross-line (high skm/vehicle)
Vehicle Utilization	Scenario 5	270	1 travel/day/vehicle (low skm/vehicle)
	Scenario 6	90	3 travel/day/vehicle (high skm/vehicle)

Note: number of HSR trips and travel length per capita, and % of HSR transport in this line among total HSR passenger transport, etc., together determine HSR development stage.

Table 5. Scenario settings for occupancy rate

Scenarios	Occupancy Rate	# of Vehicle
Baseline	70%	135
Scenario 1	40%	236
Scenario 2	100%	94

Table 6. Scenario settings for fly ash use in concrete

Scenarios	Fly Ash Use
Baseline	Status quo
Scenario G1	No fly ash; replaced by the same amount of cement

Table 7.Fly ash and cement use in concrete in the baseline scenario

Concrete in Baseline	C60	C50	C30	C25	C15	CFG
Fly Ash Use (kg/m^3)	67	99	96	95	75	140
Fly Ash Use (%)	2.7%	4.0%	4.0%	4.0%	3.3%	5.8%
Cement Use (kg/m^3)	456	346	287	286	225	150
Cement Use (%)	18.7%	14.1%	12.0%	11.9%	10.0%	6.3%

Equations for determining development stage:

Passenger transported per year by all HSR = amount of HSR trips per year per capita * travel length per travel per capita * population

Passenger transported per year by HSR between Beijing and Shanghai = Passenger transported per year by all HSR * percentage of HSR travel between Beijing and Shanghai in total HSR passenger transport (which is estimated by percentage of population in this HSR region among national population * percentage of HSR mileage in this line among total HSR mileage)

Change amount of HSR trips per year per capita, travel length per travel per capita, and % of HSR travel in this line among total HSR passenger transport to determine development stage.

Equations for determining amount of vehicle needed:

Amount of vehicle needed = Passenger transported per year by HSR between Beijing and Shanghai / (average travel length of cross-line vehicle * occupancy rate * 365 day/year * vehicle utilization rate per day * total seats per vehicle)

Equations for converting inventory of ICE HSR vehicle to China's HSR vehicle:

Conversion factor = (weight of China's HSR vehicle carriage * amount of China's HSR vehicle carriage) / (weight of Germany's ICE vehicle carriage * amount of Germany's ICE vehicle carriage)

Material and energy use per China's HSR vehicle = Material and energy use per ICE HSR vehicle * conversion factor

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