# All Aboard the Net-Zero Express: Examining the Effectiveness of China's High-Speed Rail for Decarbonizing the Transportation Industry

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**Abstract**

This work reviews the development of High-Speed Rail (HSR) in China from multiple energy perspectives and discusses its implications with regards to reaching net-zero within the country's transportation sector. This paper finds that HSR contributes to several research-backed environmental benefits, such as reductions in PM2.5 concentrations and other pollutants in both a local and nation-wide scale. In addition, HSR provides greater connectivity across the country, facilitates quick movement between the growing urban population centers, and diverts passengers from taking more polluting types of transportation, such as airplanes. However, the operation of HSR lines can have large environmental effects when considering the project full life cycle (such as construction and maintenance) and scopes two and three emissions (such as the production of the electricity powering these trains, mostly coal). Moreover, when compared to conventional electric rail, HSR pollutes more, due to the non-trivial association between energy and speed. Lastly, the over construction of passenger HSR has also disregarded the development of freight rail, shifting the transport of cargo to other more polluting yet less expensive modes, like trucking. This work concludes by recommending a series of points that the Chinese government, policy makers and transportation planners could implement in order to use HSR more effectively as a tool for decarbonizing the transportation industry in the country.

Keywords: high speed rail (HSR), environmental impact, China, net-zero, transportation decarbonization

## 1. Introduction

If one had to choose one year over the past twenty that marked a turning point for China, then that undoubtedly has to be 2008. This year was particularly meaningful for the millenary country, one central reason being the fact that the Summer Olympic Games would be held in Beijing and as such, the world, in particular the west, would have an unprecedented access to a nation seeking to grow and expand its international reputation.

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Received: 19 Jul 2022 Accepted: 25 Jul 2022 Published: 28 Jul 2022

Journal of Asian Energy Studies (2022), Vol 6, 37-47, doi:10.24112/jaes.060003

Indeed, since the opening up and reform period inaugurated by Chairman Deng, China has evolved to become one of the fastest growing countries in the planet, both from an economic and population perspective. Through its comparatively cheap labor, vast territory and natural resources, as well as the establishment of special economic regions that enabled the communist government to build an economy with capitalistic characteristics, China soon became a world leader in various industries, most notably manufacturing. Dubbed by the west an "economic miracle", China's reforms managed to lift 850 million people out of poverty between 1978 and 2014 [1], an unimaginable feat that was accompanied by a 122-fold increase in the per capita income from $379 to $46629 RMB over the same period [2]. However, these rapid economic transformations naturally induced changes in the country's population geographic distribution; indeed, more workers began migrating from the rural areas to the urban population centers, where the new jobs and wealth created from the reforms were accumulating, especially in the coastal provinces of Guangdong, Fujian, Zhejiang and Jiangsu. Naturally, this situation required an enhanced and robust transportation network that could facilitate the movement of the country's massive population not only to the large manufacturing centers, but also to places across all parts of the country.

Consequently, during the Ministry of Rail's "Mid-to-Long Term Railway Network Plan" of 2004, Chinese policy makers would call for the creation of a dedicated High-Speed Rail (HSR) passenger network, one that would connect every major city in the country in a fast, energy-efficient, and reliable way [1]. Just four years after the release of this document, in 2008, the central government was already inaugurating its first HSR line, a 120 km stretch connecting Beijing to the neighboring municipality of Tianjin [3]. Today, just 14 years later, China's HSR network spans a total length of more than 38000 km [4], making it the world's longest. In fact, two-thirds of the world's HSR track lies in China.

2008 is not just a significant year because of the Summer Olympic Games held in Beijing. Instead, 2008 is the year that marks the beginning of a railroad revolution, one that would propel an unparalleled development of transportation science and technology that would characterize the Asian nation's growth for the following decade. As Table 1 on the right illustrates, during the 2010-2019 ten-year period, the number of Chinese cities with a population exceeding 1 million inhabitants grew 29.6%, from a staggering 125 to 162 cities. At the same time, the country's population grew 4.41% to an astronomical 1.40 billion people in 2019, with 60.6% of the people living in urban centers and the remaining 39.4% in rural areas [2]. When compared to 2010, China has seen a growth of 21.44% in its urban population, but a 21.36% decline in its rural population. Thus, pursuing the development of HSR has become a paramount task for the central government, not only to facilitate this population migration, but also to connect the growing number of large urban centers.

However, as important the development of HSR is, planners should not disregard the environmental impact originating from both its construction, operation and maintenance. According to a report from the International Energy Agency (IEA), the global transportation sector has a non-negligible consumption of 19% of the world's energy and contributes to 23% of the planet's anthropogenic CO2 emissions [5]. In the context of China not only already being the world's largest emitter of greenhouse gases (producing a staggering 27% of the global emissions [1]), but also looking to expand its HSR network to an extraordinary 70000 km by 2035 with its "eight vertical and eight horizontal" structure [6], the environmental weight from railway development becomes particularly relevant. Thus, developing HSR only makes sense if it is in itself the greenest of all transportation alternatives. Fortunately, against the backdrop of the country's growing greenhouse emissions and the demonstrated impact these could have on climate change [7], President Xi has announced in 2016 a comprehensive yet ambitious plan to accomplish carbon neutrality alongside the 13th National 5-Year Plan. In essence, the goal is for China's emissions to peak by 2030 and to reach net-zero by 2060, mainly through the introduction of new technologies that would improve energy efficiency and reduce carbon intensity.

**Table 1:** *General changes in China's population and economic growth from 2010 to 2019 [2]*

| Year | 2010 | 2019 | Period % change |
|---|---|---|---|
| Cities with 1-2 million people | 81 | 98 | +20.99% |
| Cities with 2-4 million people | 30 | 44 | +46.67% |
| Cities with >4 million people | 14 | 20 | +42.86% |
| Total number of cities with >1 million people | 125 | 162 | +29.60% |
| Country population (people) | 1.34 billion | 1.40 billion | +4.41% |
| % of urban population | 49.9% | 60.6% | +21.44% |
| % of rural population | 50.1% | 39.4% | -21.36% |
| GDP (100 million RMB) | $401202 | $990865 | +146.97% |
| GPD per capita (RMB) | $29992 | $70725 | +135.81% |

## 2. Energy Efficiencies and the Environmental Benefits of HSR

According to a report by the IEA [8], rail is one of the most efficient forms of passenger travel, transporting today 8% of the world's travelers, but only consuming 2% of the industry's overall energy use. As such, rail naturally is an excellent green alternative to other modes of transportation [9], and makes particular sense in China, given its population density and geographic distribution [10]. Furthermore, its development can act as well as an equilibrating power, bringing growth and wealth to less developed areas of the country and helping with the promotion of regional hubs [9].

Effectively, railway construction is greatly interweaved with the economy and the environment. More specifically, according to data from the National Bureau of Statistics of China, the transportation industry represents about 4.3% of the country's GDP, but accounts for 9% of the country's energy consumption [2, 11]. Table 2 below maps how these two percentages changed over the 2010-2019 ten-year period. As can be seen, while the industry's GDP contribution stayed relatively constant over the last ten years, its energy consumption increased, meaning that the energy intensity ratio (energy per unit of GDP) has also increased. Hence, the development of passenger HSR other than that of conventional rail only makes sense if it can be used as a means to reduce the emissions from transportation in the country. The question then is, does HSR actually achieve this goal?

### 2.1. Energy efficiencies and environmental benefits

There have been multiple studies performed in the past that examine the energy efficiencies of HSR and the various environmental benefits it could bring for China as a whole. For instance, according to the research performed by Yang and his colleagues [12], implementing a large-scale passenger HSR network on the country can reduce the emissions from rail by 7.35% due to technological innovation and resource allocation. This result is in agreement with that from another study which found that on average HSR consumes 29% less energy than conventional railway systems [13].

**Table 2:** *Energy consumption of China's transportation sector from 2010 to 2019 [2]*

| Year | % of energy consumed by transportation industry | % of petroleum consumed by transportation industry | % GDP contribution by transportation industry |
|---|---|---|---|
| 2010 | 7.51 | 34.13 | 4.60 |
| 2011 | 7.86 | 35.09 | 4.50 |
| 2012 | 8.32 | 37.27 | 4.40 |
| 2013 | 8.34 | 36.57 | 4.40 |
| 2014 | 8.35 | 37.69 | 4.40 |
| 2015 | 8.87 | 36.92 | 4.40 |
| 2016 | 9.03 | 36.65 | 4.40 |
| 2017 | 9.24 | 36.65 | 4.50 |
| 2018 | 9.24 | 36.53 | 4.40 |
| 2019 | 9.01 | 34.28 | 4.30 |

In addition, increasing the number of HSR frequencies can also lead to reduced concentrations of PM2.5 [14]. In 2019, 180 of 336 surveyed cities in China possessed concentrations of PM2.5 that exceeded the required air standards. Thus, the investigations carried forward by Zhang and his team [14] examined HSR frequencies among these cities and specifically tried to determine if there was any correlation with the elevated PM2.5 concentrations. Zhang's work not only found that air pollution improved at the origin and destination cities, but also along every station on the lines [14].

On a similar study performed by Jia et al. [15], 275 cities at the prefecture level in China were examined to determine the impact that HSR service intensity could have on the locally produced greenhouse gas emissions. Succinctly, this work found that higher levels of HSR service reduced the local urban pollution (although mostly due to transportation mode substitutions), and for every 100 HSR services into a city, CO2 emissions could be reduced locally by 0.14%.

## 2.2. Rail against planes?

Another area in which HSR can act as an effective means for decarbonizing the industry is by diverting passengers from using other more polluting modes of transportation, most notably aviation. Indeed, according to a report from the IEA [8], railways require on average 12 times less energy than airplanes and emit about 10 times less.

Today, China simultaneously possesses both the world's second largest civil aviation market as well as the world's largest HSR network, the latter of which can be seen in Figure 1. Given the country's size and its large number of geographically dispersed population centers, rail and aviation both serve a critical role, sometimes complementary, in transporting citizens to all corners of the country. This is particularly true in high density routes, such as Beijing to Shanghai, where on top of the dozens of flights available every day, there are 42 HSR trains operating the segment, each with a capacity to carry up to 1200 passengers [16].

Due to congestions in airspace, on top of the central government's push towards the expansion of the HSR network, rail has become over the past 10 years a very strong competitor to commercial aviation in air routes covering less than 800 km [16]. And for those routes that are served by both rail and airplanes, demand has been found to be more price elastic, meaning that consumers will often choose the cheaper alternative, most of the times to take the train [14]. Using the city of Hong Kong as an example, the recently inaugurated high-speed rail link already connects the city to 44 destinations in the mainland, and average train ticket prices have been consistently at about half that of the airplane alternative [17]. Overall, it is expected that by 2025, 80% of all domestic routes in China will be overlapped by high-speed rail [14].

Now, despite the promising state of the country's HSR network and its strong ability to compete with the domestic airlines, civil aviation in China is still set to continue growing at unprecedented rates. By 2029, it is expected that the East Asian nation will be the largest civil aviation market [18, 19], and by 2050 emissions from the industry could quadruple. To provide a point of comparison, in 2018 alone, China's domestic aviation sector was responsible for the emission of 95 million tons of CO2e, 13% of the global emissions from aviation [18, 19]. Thus, developing HSR must also be accompanied with policy that discourages passengers from travelling by plane, at least in short routes.


**Figure 1:** *China's high-speed rail infrastructure network. Source: Wikimedia Commons.*

## 3. Mapping the Emissions

As can be seen, expanding HSR has a number of demonstrated benefits for the environment, and this makes the Chinese general public very supportive of it [20]. However, many of the studies cited in the previous section fail to take into consideration the full life cycle of a HSR project beyond just the operation, often omitting the construction and maintenance stages, resulting in misleading conclusions. For example, the construction of the Beijing-Shanghai HSR line required twice as much concrete as the Three Gorges Dam and 120 times the amount of steel used in the Beijing National Stadium [20], representing tremendous costs to the environment. Therefore, one can only ask, is the efficiency provided by the high-speed train lines, in the long run, going to offset the costs imposed by their construction? How easy is it to even offset the carbon emissions from rail construction? One concept that has been put forth by economic experts studying China's growth is that of railway Keynesianism, which essentially describes the situation where constructing new railway infrastructure drives the demand for more concrete and steel, which in turn pushes for more railways in the first place [21]. These two industries consume non-negligible amounts of energy and pollute enormously [4], yet their environmental footprints are not normally considered when thinking of HSR.

To further complicate matters, many of China's HSR routes today are running at idle capacity, which is certainly problematic when 26% of the country's network is composed of HSR tracks [21]. In fact, the passenger density for the Beijing-Shanghai HSR line (the busiest) is just 17 million passenger-kms, while that of Japan's Tokaido Shinkansen (running between Osaka, Kyoto and Tokyo) is twice as much [21]. Considering that building HSR is on average three times more expensive than building conventional rail [22], then does it make sense to continue its expansion given the current ridership rates? Or wouldn't it make more sense to invest instead in renewable technologies that could replace the coal that is powering the electric railway networks across the country?

In this section, HSR will be explored in greater detail by focusing specifically on the full life cycle of the project and by also considering factors such as ridership and even the intrinsic engineering and aerodynamics of high-speed trains.

## 3.1. Life cycle analysis

There have been some studies in the past that performed life cycle analysis on China's HSR. One of them has been that of Wang and his colleagues [23], which looked into understanding the specific environmental consequences from both the construction and operation of HSR. For example, on the first category, their research argues that there are costs associated with the loss of vegetation, topography destruction, farmland occupation, water environment pollution, in addition to noise from the construction machinery and vehicles that are often neglected. On the second category, Wang argues that factors such as waste and noise pollution are also not normally cited as side effects from the operation of HSR but are certainly significant. And while it may be true that using HSR may reduce pollution, Wang et al [23] found that this is mostly the case on the coastal provinces (since emissions are shifted towards the west and central areas of the country [11]).

Continuing on this work, the investigations from Lin et al. [3] focused on tracking the environmental footprint of the Beijing-Tianjin line (the first HSR line inaugurated in 2008) by considering its full life cycle. Their work found that the construction of bridges had the highest environmental footprint, which is an interesting result given that bridges compose 83.8% of the line's 120 km length. This is not surprising given that bridges, which are made of pre-stressed concrete, are key for the operation of HSR, since they enable a straight and leveled structure. Lin et al. [3] also found that metal smelting and rolling had considerable environmental effects, followed by the manufacturing of the transport equipment and the non-metallic mineral production.

On a later study, Lin and the team [6] performed an even more granular life cycle assessment on the Beijing-Shanghai HSR line. Succinctly, their work found that the operation of the line accounted for 71% of all the carbon footprint, followed by 20% from construction and 9% from the maintenance. In addition, similarly to the Beijing-Tianjin study, in the construction stage, bridges occupied the highest carbon footprint (and notice that similarly to the Beijing-Tianjin line, of the 1318 km connecting Beijing-Shanghai, 86.5% of the HSR tracks are laid in bridges). Lin's study also attempted to characterize the different emissions scopes, and found that Scope 1, the direct carbon emissions from operation, and Scope 3, the carbon emissions from construction and maintenance, were lowest, at 5% and 25% of the footprint. In contrast, Scope 2, the indirect carbon emissions originating from the production of electric power, were the highest, at 70% of the footprint; this result is not surprising, given how carbon-intensive China's energy mix for electricity generation is. All in all, after incorporating the full life cycle, Lin's work found that the average annual carbon footprint of the Beijing-Shanghai HSR line was 3002 kt of CO2 (for the 2011-2014 period). To put this number into context, single use plastic bags generate 1.58 kg of CO2e [24]. As a result, 3002 kt of CO2 corresponds to 1.9 billion plastic bags.

### 3.2. Ridership, debt and freight

Another problem with China's HSR that had been alluded above was that of its under-utilization [22], especially for the trains that run outside the Beijing-Shanghai and Beijing-Guangzhou corridors. A commonly quoted example is that of the 1776 km long Lanzhou-Xinjiang line along the historic Silk Road, which was built to withstand a capacity of 160 daily pairs of trains, but only has 4 pairs running. This example casts doubt in China's HSR planning effectiveness, given that the income generated from this route is not enough to even pay for electricity costs due to the line's low ridership. Instead, because of the line's long distance and thin demand, an air service would be much better suited to cover the segment. But even beyond this extreme example, what is even more interesting is the fact that the Beijing-shanghai line, despite being the most profitable, only sees a 4% return on invest [4]. Hence, this situation leads one to question, given the high investment that developing HSR implies, if most lines are unprofitable, then is building more HSR the most efficient use of financial and natural resources for China to meet its decarbonization and transportation goals?

Debt from railways in China has grown from 70 billion (USD) in 2005 to 900 billion (USD) in 2021 [17]. Provincial route operators have fallen on a debt trap, due to the difficulties in generating profit and repaying the interest from building HSR lines [21]. China's massive pursuit of HSR has come at a high price, despite the fact that the country possesses 162 cities with a population exceeding 1 million people [2].

In addition, the country's over deployment of passenger HSR has shifted the domestic transportation structure, given that HSR has overshadowed the development of conventional rail for freight transportation [4]. Indeed, over the past 10 years, the cost of rail freight transportation has increased, in part due to the reduced number of investments in the area, in part also due to the rail controlling entities charging freight more due to the operation losses induced from the passenger HSR system. These changes in passenger and freight movements through rail can be seen more concretely in Table 3 below, while table Table 4 illustrates the macroscopic changes that took place over the ten-year period between 2010 and 2019.

**Table 3:** *Changes in rail passenger and rail freight transportation from 2010 to 2019 [2]*

| Year | % of freight (tons-km) carried by rail | % of rail that is electrified | Market share (passenger-km) occupied by rail |
|---|---|---|---|
| 2010 | 19.49 | 35.86 | 31.41 |
| 2011 | 18.49 | 36.80 | 31.02 |
| 2012 | 16.79 | 36.37 | 29.39 |
| 2013 | 17.36 | 34.91 | 38.43 |
| 2014 | 15.15 | 33.01 | 39.24 |
| 2015 | 13.32 | 61.74 | 39.79 |
| 2016 | 12.75 | 64.76 | 40.24 |
| 2017 | 13.66 | 68.19 | 41.01 |
| 2018 | 14.08 | 70.01 | 41.34 |
| 2019 | 15.14 | 71.77 | 41.60 |

As can be seen, over the 2010-2019 period, the volume of freight carried by rail increased by only 9.18%, well-under the period's 40.58% total increase in total freight volume across all modes of transportation. In essence, this translated into a decrease in the percentage of freight that was carried by rail of 22.34% over the ten-year period. In comparison, the number of passengers

**Table 4:** *Macroscopic changes in China's rail passenger and rail freight transportation from 2010 to 2019 [2]*

| Year | 2010 | 2019 | Period % change |
|---|---|---|---|
| Rail freight (tons-km) | 27644 | 30182 | +9.18% |
| Total volume of freight (tons-km) | 141837 | 199394 | +40.58% |
| % of freight carried by rail | 19.49% | 15.14% | -22.34% |
| | | | |
| Rail passengers (passenger-km) | 8762 | 14706 | +67.84% |
| Total volume of passengers (x1oooo) | 27894 | 35349 | +26.73% |
| Market share occupied by rail | 31.41% | 41.60% | +32.44% |

travelling by rail increased by 67.84%, beating the overall volume of passengers travelling across all modes of transportation, which had increased by 26.73%. Additionally, as Table 4 shows, the market share occupied by rail increased by 32.44%. These trends can be seen graphically in Figure 2, which combine the data from Table 3 and Table 4, as well as in Figure 3 below.

As a matter of fact, as the plot in [a] shows, the increase in the number of passengers that chose to take rail as opposed to other modes of transportation was followed by a decrease in the relative amount of freight that was transported by rail. Another trend that is shown in plot [b] and Figure 3 below is that beginning in 2015, the percentage of the railway network that was electrified grew enormously, from little above 30% to beyond 70%. However, these plots also indicate that the increase in electrification was only followed by a very small decline in the use of petroleum in the transportation sector as a whole, a somewhat contradictory trend. In all cases, the curve denoting the amount of energy consumed by the transportation sector also remained constant over the ten-year period. Overall, what these statistics show is that in the first place, expanding HSR encouraged more rail passenger travel but less rail freight transport. In addition, despite the electrification efforts, the amount of petroleum consumed by the sector remained the same, a result which can be explained by shifting freight towards other, less efficient, less environmentally friendly, more expensive modes of transportation, like trucking [11,21,22].

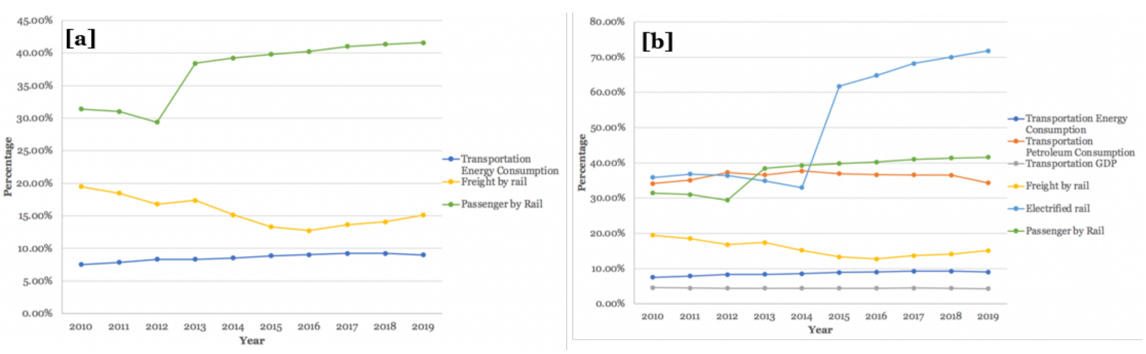


**Figure 2:** *Mapping changes in China's rail passengers and rail freight [a] and the global picture with energy consumption and GDP contribution of the sector [b] from 2010 to 2019. Source: [2]*

## 3.3. High speed operations

One non-negligible aspect about the energy consumption of passenger HSR is related to the actual operation speed of the trains and the scheduling (or more precisely, the stopping frequencies).

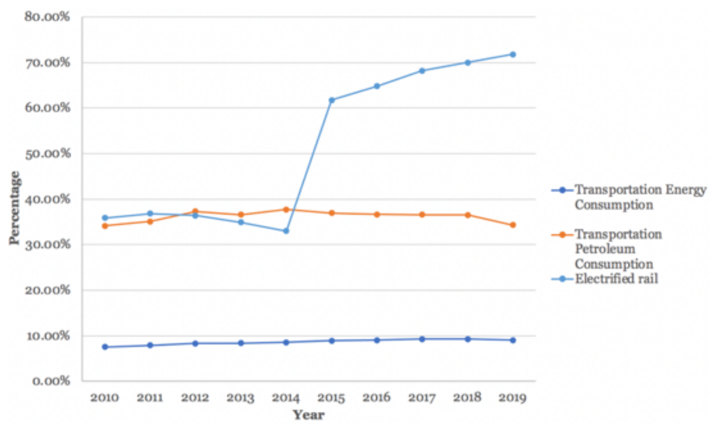


**Figure 3:** *Mapping changes in energy consumption and GDP contribution of the transportation sector from 2010 to 2019. Source: [2]*

The relationship between energy and speed is fairly straightforward to see; increases in operation speed naturally leads to increases in the overall energy consumed, although the dependency is not linear but quadratic. As the study performed by Hasegawa and his colleagues shows [25], increasing the train operation speed causes more drag, which is proportional to the square of the velocity. As a result, just a marginal change in speed can lead to an even greater change in drag and thus the energy required to overcome it. Moreover, Hasegawa's study [25] also finds that operating a HSR line at lower speeds than the maximum, while increasing journey time, has the effect of decreasing the overall amount of energy used.

The dependency between energy and the scheduling is more interesting, since this relationship concerns the number of stops in a schedule and the length between each stop. For instance, taking the Shanghai-Hangzhou line as an example, Feng and his team [26] modelled energy consumption for different schedules with a different number of stops. Their work found a number of fascinating results, one of them being that in order for a certain target operation speed to be reached, segments must have a specific minimum length [26]. As a result, routes with more stops in them have on average shorter segments, already limiting the maximum operation speed. Not surprisingly, Feng et al. came to the conclusion that non-stop routes consume less energy than those with stops, and as was argued above, those routes that operated at lower speeds required also less energy. In the context of China's railway network, there is a variety of non-stop and multi-stop services, usually listed as G-trains (which are mostly operated in non-stop routes at a maximum speed of 380 km/h), D-trains (second fastest, operated at 200 km/h), and C-trains (frequent, inter-city services) for HSR, and then Z, T and K-trains (each with more stops and lower speeds) for regular rail. Thus, many of these scheduling considerations apply to the energy consumption of China's HSR railways.

## 4. Conclusion

This work has examined and reviewed the development of HSR in China from multiple energy perspectives. In the one hand, this work found that HSR contributes to several environmental benefits, such as a research-backed reduction in PM2.5 concentrations and other pollutants in both a local and nation-wide scale. In addition, HSR provides greater connectivity across the country, facilitates quick movement between the growing urban population centers, and is slowly diverting passengers from taking more polluting types of transportation, such as aviation. However, in the other hand, HSR operation can have large environmental effects when considering the full life cycle (such as construction and maintenance), and also pollutes more than conventional rail, due to the non-trivial relationship between energy and speed. Furthermore, the over construction of passenger HSR, in part due to pursuits by local governments to boost their GDP [22], has also disregarded the development of rail freight. This condition, naturally, has shifted the transport of freight to other more polluting yet less expensive modes, like trucking.

This work ends by recommending a series of points that the Chinese government, policy makers and transportation planners could implement in order to use HSR more effectively as a tool for decarbonizing the transportation industry. These include:

- Building more conventional electric trains. These trains can have a life cycle footprint that may be similar to HSR, but the overall cost for developing these projects is much lower. As a result, this can leave extra funds to develop more renewable power technologies.
- Pursuing the development of renewable power. Whether it is for HSR or traditional electric trains, most of the electricity used to power them comes from a carbon-intensive mix of energies, which contributes to Scope 2 emissions. As a result, the development of HSR must happen in parallel to that of a green and sustainable grid.
- Encouraging the development of intermodal modes of transportation. As the Lanzhou-Xinjiang railway example illustrated, HSR may not be the most efficient mode for long distance routes. Instead, HSR makes more sense in shorter routes, or those that take place between large urban population centers, such as between Beijing, Shanghai and Guangzhou. As a result, combining train with flight or even bus services can lead the best utilization of each modes of transportation and lead towards a decrease in emissions.

HSR construction is set to continue growing, with the goal by 2035 being reaching a length of 70000 km. In the context of China's environmental goals and the 2060 target towards net-zero emissions, it is paramount to consider the full environmental effects that more HSR could induce in the country. And while this work has shown that HSR brings a number of concrete environmental benefits, it has also demonstrated that it contributes directly and indirectly to the country's emissions, quite significantly. Only the future will tell whether the country that underwent the "economic miracle" will also experience an energetic and climate miracle.

**Declaration of interest:** None

## References

[1] World Bank Group. *China Systematic Country Diagnostic*. 2020.

[2] National Bureau of Statistics of China. *China Statistical Yearbook*. China Statistics Press, 2020.

[3] Lin J, Cheng S, Li H, Yang D, Lin T. Environmental footprints of high-speed railway construction in China: A case study of the Beijing–Tianjin Line. *International Journal of Environmental Research and Public Health* 2020:17:105.

[4] Pike L. How green Is China's high-speed rail? *China Dialogue*. 2021. https://chinadialogue.net/en/energy/11174-how-green-is-china-s-high-speed-rail/.

[5] Yin X, Chen W, Eom J, Clarke LE, Kim SH, Patel PL, Yu S, Kyle GP. China's transportation energy consumption and CO2 emissions from a global perspective. *Energy Policy* 2015:82:233-248.

[6] Lin J, Li H, Huang W, Xu W, Cheng S. A carbon footprint of high-speed railways in China: A case study of the Beijing-Shanghai line. *Journal of Industrial Ecology* 2019:23:869-878.

[7] IPCC. *6th IPCC Report: Summary for Policymakers. Climate Change 2021: The Physical Science Basis*. 2021.
[8] International Energy Agency. *Rail*. 2021.
[9] Turner, J. Is High-Speed Rail the Fast Track to Transport Decarbonisation? *Railway Technology*. 2020. https://www.railway-technology.com/features/high-speed-rail-sustainability/
[10] Zhang F, Wang F, Yao S. High-speed rail accessibility and haze pollution in China: A spatial econometrics perspective. *Transportation Research Part D: Transport and Environment* 2021:94:102802.
[11] Xu X, Xu H. The driving factors of carbon emissions in China's transportation sector: A spatial analysis. *Frontiers in Energy Research* 2021:9:225.
[12] Yang X, Lin S, Li Y, He M. Can high-speed rail reduce environmental pollution? Evidence from China. *Journal of Cleaner Production* 2019:239:118135.
[13] Álvarez AG. Energy consumption and emissions of high-speed trains. *Transportation Research Record* 2010:2159:27-35.
[14] Zhang Q, Yang H, Wang Q. Impact of high-speed rail on China's Big Three airlines. *Transportation Research Part A: Policy and Practice* 2017:98:77-85.
[15] Jia R, Shao S, Yang L. High-speed rail and CO2 emissions in urban China: A spatial difference-in-differences approach. *Energy Economics* 2021:99:105271.
[16] Wang J, Huang J, Jing Y. Competition between high-speed trains and air travel in China: From a spatial to spatiotemporal perspective. *Transportation Research Part A: Policy and Practice* 2020:133:62-78.
[17] Bloomberg. 2016. https://www.bloomberg.com/news/features/2018-09-17/china-s-bullet-trains-are-coming-for-hong-kong-s-airlines.
[18] Bo X, Xue X, Xu J, Du X, Zhou B, Tang L. Aviation's emissions and contribution to the air quality in China. *Atmospheric Environment* 2019:201:121-131.
[19] Gabbatiss J. Emissions from Chinese aviation 'could quadruple by 2050'. *Carbon Brief*. 2021. https://www.carbonbrief.org/emissions-from-chinese-aviation-could-quadruple-by-2050
[20] He G, Mol APJ, Zhang L, Lu Y. Environmental risks of high-speed railway in China: Public participation, perception and trust. *Environmental Development* 2015:14:37-52.
[21] Desai D. China's high-speed railways plunge from high profits into a debt trap. Observer Research Foundation. 2021. https://www.orfonline.org/expert-speak/chinas-high-speed-railways-plunge-from-high-profits-into-a-debt-trap/
[22] Zhao J. https://sa123.cc/747gbh1xyygwmpivkvij.html
[23] Wang S, Zhou H, Hua G. Is the high-speed rail opening environmentally friendly? Taking the difference-in-differences test in Jiangsu, China. *Complexity* 2020:2020:7154076.
[24] Fry CE. Life cycle assessment of supermarket carrier bags. 2011.
[25] Hasegawa D, Nicholson GL, Roberts C, Schmid F. The impact of different maximum speeds on journey times, energy use, headway times and the number of trains required for phase one of Britain's high speed two line. *WIT Transactions on the Built Environment* 2014:135:485-496.
[26] Feng X, Sun Q, Liu L, Li M. Assessing energy consumption of high-speed trains based on mechanical energy. *Procedia-Social and Behavioral Sciences* 2014:138:783-790.