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Editorial

High-speed rail and carbon emissions

1. HSR and environment: issues and policy significance

Climate change has become an issue that has aroused much public concern around the world in recent years. Greenhouse gas (GHG) emissions, primarily CO2 emissions, that are attributable to human activities have been considered as a major contributor of global warming and climate change. It is estimated that transportation accounts for around one-fifth of global CO2 emissions (Zhang et al., 2004; Sims et al., 2014; IEA, 2021) of which road transport takes the lion's share. On the per passenger-km basis, high-speed rail (HSR) is generally claimed to emit less CO2 or CO2-equivalent than aircraft, private cars and coaches, while it is expected to consume more energy, due to higher speed, and hence cause more GHG emissions than conventional railways if both are powered by the same source of electricity (Refer to Jiang et al. 2021, for a detailed review). This makes HSR a popular topic among scholars and policy makers, considering that one major objective of developing HSR, among others, is to reduce the negative environmental impacts, including GHG emissions, of transportation. In China, which has by far the largest HSR network in the world and is still investing continuously in this transportation mode, a key national policy is to reach carbon peaking by 2030 and carbon neutrality by 2060. Expectedly, numerous studies on HSR's environmental impacts in the context of China have emerged over the past decade.

The answer to the questions of whether and to what extent the development of HSR can achieve a net emission reduction is far from clear. The ability of HSR to reduce GHG emissions mainly stems from the traffic diversion (also called substitution) effect. Traffic diversion refers to the situation when the introduction of HSR, a new transportation mode, causes passengers of other transportation modes to switch from these existing modes to HSR. As HSR can effectively attract passengers away from airplanes on routes below 1,000 km, conventional trains, inter-city coaches and private cars (Refer to Givoni and Dobruszkes 2013, Zhang et al. 2019, for comprehensive reviews), the immediate conjecture is that net CO2 emissions will reduce if HSR has a lower emission rate[1] than the other modes. However, this potential emission reduction due to traffic diversion is only part of the story, as several issues can potentially pivot the result. First, diverting traffic from conventional rail to HSR may increase emission because in many cases, for example in China, some conventional passenger trains are powered by electricity as well. Second, the introduction of HSR may induce new travel demand by either providing more alternatives, better access and on-time performance, or feeding traffic for other transportation modes, especially air flights. This newly induced demand for HSR trips, which is called traffic generation effect of HSR, is expected to serve as a source of emission growth. Third, most of the existing work (10-15 years ago in particular) focused on CO2 emissions at the operation stage, i.e., what comes out of the "tail pipe" of a vehicle (rolling stock, aircraft, automobile). Apart from operation, activities such as infrastructure construction and vehicle manufacture also generate emissions. To deal with this issue, the more recent life-cycle analysis (LCA) is an improvement. Consequently, for developing a new HSR line, emissions generated during the other activities might outweigh the emission reduction at the operation stage. As LCA has become more common in assessing HSR's environmental impacts, in the next two sections, we discuss existing studies using LCA to evaluate the life-cycle CO2 emissions of HSR and future research directions of applying this approach on the topic.

2. Existing studies on life-cycle emissions of HSR

LCA is widely used to assess environmental impacts of a transportation infrastructure throughout its life cycle. In the context of CO2 emission assessment, it measures the life-cycle emissions by taking into account emissions from the time when the infrastructure is being constructed to the end of the infrastructure's expected lifespan. All activities and functions associated with providing the

[1] Emission rate refers to the amount of CO2 emission from moving one passenger or one seat from city A to city B. In some cases, one may also consider it as the amount of CO2 emissions from moving one passenger or one seat for one kilometer.

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transportation infrastructure and services as well as supply of related materials can cause emissions and thus are expected to be included when assessing the life-cycle emissions of the infrastructure in concern. As summarized by Jiang et al. (2021), LCA is supposed to count emissions from three groups of activities during the lifespan of a transportation infrastructure: (i) manufacture, maintenance and operation of vehicles, (ii) construction, maintenance and operation of infrastructure, and (iii) energy generation such as the production and distribution of fuel and electricity. Ideally, both emissions directly released from the abovementioned activities and those indirectly generated from producing and distributing input materials, such as concrete and steel should be included (e.g., Chang et al. 2019, Cheng et al. 2020). The one-shot GHG emissions from constructing an infrastructure and producing a vehicle will be evenly allocated throughout the lifespan of the infrastructure and the vehicle, respectively. The resultant annualized values will be added to various years' emissions from operations to generate total emissions of each individual year. This information can be further used to find out whether and from which year during its lifespan HSR can achieve net reduction of GHG emissions.

Most studies that assess HSR's CO2 emissions with LCA pay more attention to emissions from HSR alone while largely ignoring the traffic diversion and generation effects in a multi-modal context. Studies that apply scientific methods to quantify these traffic impacts, on the other hand, tend to confine the emission assessment to the operation of vehicles. Nevertheless, we are aware of several studies that incorporate HSR's traffic diversion effect into LCA by imposing some simplifications in the assessment process (Jiang et al., 2021). For example, these studies usually do not estimate traffic diverted from other modes to HSR but make assumptions on the amount of modal shift, as they aim at finding out the amount of modal shift needed to environmentally justify the construction of HSR, instead of quantifying the impacts ex post. In addition, infrastructure construction and vehicle manufacture of the other transportation modes are assumed to be constant, and hence only the operation stage is considered when estimating avoided emissions due to traffic diversion.

The only exception which aims to deal with the issues mentioned above, as far as we know, is the study conducted by Chen et al. (2021). Chen et al. took a counterfactual approach to quantify diverted and generated traffic for the Shanghai-Beijing HSR ex post. The traffic diverted to HSR is defined as the difference of the projected traffic and actual traffic of each non-HSR mode (air, highway and conventional railways). The traffic generation effect is reflected by the difference between actual HSR traffic and the sum of diverted traffic from the other modes. Another noteworthy feature is that Chen et al. (2021) consider the effect of avoided infrastructure expansion and vehicle production of non-HSR modes. Although the former is found insignificant, the later can effectively offset a trunk share of emissions from manufacturing HSR rolling stocks. As conventional rail was the main source of traffic diversion in the early years of HSR operation, CO2 emissions of vehicle operation alone actually increased first and then decreased after air and road's share of diverted traffic improved. Overall, the Shanghai-Beijing HSR is expected to achieve net CO2 reduction after 26 years of operation.

Once LCA is applied, HSR's potential for emission reduction will be significantly discounted, because comparing with air and road, HSR emits substantially more GHG at the construction stage, especially when tunnels, bridges and viaducts are involved. Studies applying LCA in general question the HSR's emission reduction capability since a high level of traffic diversion is crucial (e.g., Miyoshi and Givoni 2013). But the results are case and context dependent, as some studies find HSR can effectively reduce emissions. For example, Robertson (2016) finds in an LCA of proposed Sydney-Melbourne HSR that a 18% emission reduction can be achieved in 2056 comparing with the air transport-only scenario. This result is based on a series of assumptions. In particular, the lifespan of the HSR is from 2026 to 2056 and at most 38% of air trips will be shifted to HSR which is said to be a reasonable number based on several modal shift studies.

3. Assessment of existing studies and future research directions

A complete LCA by incorporating traffic diversion and traffic generation effects can be difficult, as it requires not only complicated assessment on the emission rates of each activity for each transportation mode but also rigorous modeling of the substitution and complementarity relationship among various transportation modes. Thus, existing studies mainly build upon key parameters estimated by other sources and make various assumptions according to the context. In general, it is difficult to trace the analysis and identify reasons behind differentiated findings and in many cases the results are not ready for comparison across studies.

Even when using the same information and approach for travel demand and emission calculation, quite a few other aspects could affect the findings. For example, the multi-modal context makes it is usually unclear how much should be the appropriate lifespan assumed for each infrastructure and vehicle, and in many cases all transportation modes are assumed to have the same lifespan.[2] Vehicle load factor (or traffic density) is also unclear especially for ex ante assessment and mostly assumed by the researchers, but it can substantially affect vehicle emissions per passenger-km. The change in the scope of emission-generating activities covered in the study may pivot the conclusion. We already see the difference caused by the inclusion of emissions from infrastructure construction and vehicle manufacture in the literature, but it seems that the maintenance of infrastructure and vehicle is seldom explicitly included in LCA, though widely mentioned. Considering that extant rail track requires continual maintenance to maintain steady and safety state and carbon released from this activity may also correlate with the HSR travel demand, this leads to one possible future research direction.

Unlike the traffic diversion effect, the traffic generation effect is less straightforward to model. Existing studies assume that traffic generation only occurs in the form of HSR trips (e.g., Chen et al. 2021, Robert, 2016), as the other transportation modes which compete with HSR in the same route market are expected to lose traffic. However, as empirically found by Gu and Wan (2020),

[2] Some studies assume different lifespans depending on the type of infrastructure, e.g. Chen et al (2021).

air traffic on routes without HSR entry can also increase if HSR provides opportunity to feed air flights on these routes. However, city-pairs and markets without HSR entries are entirely excluded from existing LCA, causing a possible overestimation on HSR's environmental benefit. Thus, another possible direction for future study is to develop a better way to incorporate traffic generation effect, especially effects on other transportation services complementing the focal HSR service.

In the future, possible changes related to energy sources can invalidate current assessment. These changes can be uncertain and complex, as quite a few driving forces are working simultaneously. First, fuel prices are rising, and its impact on travel cost could vary in transportation mode. It is unclear how these changes can affect traffic distribution and the total travel demand in the multimodal context. Second, the overall trend towards sustainable energy and power generation technologies adds some doubt to the issue. Regulatory changes towards net-zero GHG emissions may cover various transportation sectors. For example, the legislation revision by European Commission under the "Fit for 55" plan includes phasing out the free allowance allocation to aviation under the EU emission trading system (ETS), enhancing renewable energy targets and developing alternative fuel infrastructure for transportation sector, achieving full transition to zero-emission (such as electric) car sales, increasing the acceptance of sustainable aviation fuels, etc. The LCA conducted by Miyoshi and Givoni (2013) on the London-Manchester HSR reveals little extra environmental benefit of HSR in scenarios of improved energy efficiency. However, comparing with the case of no HSR and traditional energy sources, Robertson (2018) finds in a study on Sydney-Melbourne HSR that the joint adoption of HSR and renewable energy technologies can achieve emission reduction up to 24% (49%, respectively) if the cleaner energy is adopted on HSR (air, respectively), and 69% of reduction can be achieved in year 2056 if both modes adopt renewable energies and the traffic diversion rate reaches 60%. The complexity of the issue is not difficult to imagine. Taking the adoption of hydrogen technology by aviation as an example. While hydrogen is totally clean and green during the operation, if we consider the life cycle of producing hydrogen including production and transportation, this may not be the case. The equipment used in the production of hydrogen is made from iron, steel, and bronze, implying a large amount of CO2 emissions. In addition, the electricity is one of the most important inputs in a number of hydrogen production technologies, and electricity production is quite polluting in some countries (e.g., burning coal). Thus, if the carbon capture and storage technology are not widely used in the industries, it might not be apt to say that hydrogen is a green technology. In the long term, to avoid relying on the expensive and high-emitting road transport, an extensive pipeline system needs to be developed to transport hydrogen from manufacturing plants to an airport. Besides, existing aircraft would have to be replaced with those using hydrogen ahead of the regular aircraft retirement schedule. All these activities, such as development of pipeline system and manufacture of new aircraft, not only have cost concerns but also contribute to CO2 emissions and, in turn, should have implications on the LCA of HSR development.

In sum, the multimodal interaction leads to complexity and uncertainty in assessing the CO2 emission impacts of HSR. While LCA provides a comprehensive assessment by including activities throughout the lifespan of the transportation infrastructure, a few important aspects have yet been well embedded in the existing studies using this approach. To achieve a better understanding on HSR's emission impacts, future research should not only incorporate the estimation of traffic diversion and traffic generation effects into LCA, but also pay more attention to the changes in energy sources in related transportation modes as well as the subsequent influence of such changes on the LCA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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