

## **Full Steam Ahead: Paving the Track to Sustainable Transit**

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Vulnerable populations, such as middle-aged and older adults, face significant health risks stemming from environmental issues like air pollution. Research has shown that components of air pollution, such as particulate matter (PM<sub>2.5</sub>) and nitrogen dioxide (NO<sub>2</sub>), adversely affect cognitive function in these populations, contributing to cognitive impairment and dementia (Gatto et al., 2014). This underscores the urgency of reducing urban air pollution to protect public health. One promising solution to mitigate emissions that cause air pollution is the implementation of high-speed rail (HSR).

HSR revolutionizes passenger rail transport with its exceptional speed, typically exceeding 250 km/h (155 mph), achieved through dedicated tracks, streamlined trains, and advanced infrastructure (Vickerman, 2015). Compared to conventional trains, HSR presents a host of advantages. Foremost is its speed, drastically reducing travel time between destinations. Efficiency is another hallmark, with HSR often boasting higher energy efficiency and lower emissions per passenger kilometer, up to 16.8%, especially when powered by renewable electricity (Watson, Ali, & Bayyati, 2022). The reliability of HSR systems surpasses that of traditional trains due to tracks dedicated specifically to HSR and advanced signaling. Moreover, passenger comfort is prioritized, offering spacious seating, onboard amenities, and smooth rides even at high speeds. Economically, HSR stimulates development by improving city connectivity, fostering tourism, and generating employment (Vickerman, 2018). Environmental benefits are significant as well, as HSR provides a sustainable alternative to air and road travel, curbing greenhouse gas emissions and mitigating congestion (Sun et al., 2017). Overall, high-speed rail stands as a modern, efficient, and eco-friendly mode of transportation that enhances mobility and connectivity while minimizing environmental impact.

HSR presents a transformative opportunity in the realm of transportation, offering a sustainable alternative to conventional modes of travel such as cars and planes. The transportation sector accounts for approximately 24% of global energy-related CO<sub>2</sub> emissions, with road transport being the largest contributor; additionally, aviation and maritime shipping contribute to around 2-3% of global greenhouse gas emissions, exacerbating environmental degradation and air quality issues (Baig et al., 2016). With the transportation sector being a significant contributor to carbon emissions and environmental degradation, the adoption of HSR holds promise for mitigating these impacts (Kamga & Yazici). In the context of the United States, where transportation dependency on oil remains high and greenhouse gas emissions from the sector are substantial, the exploration of HSR as a viable solution becomes imperative (Kamga & Yazici). This paper will delve into the multifaceted aspects of HSR's potential to address environmental, social, and economic challenges, highlighting its role in fostering sustainability within transportation systems.

The paper will commence by examining the current state of transportation in the United States, emphasizing its heavy reliance on oil and the associated greenhouse gas emissions (Kamga & Yazici). Subsequently, the cultural and economic significance of automobiles and air travel will be explored, shedding light on the environmental costs incurred by these modes of transportation (Kamga & Yazici). Following this, attention will be directed towards the institutional dimensions of HSR in the U.S., including the challenges and opportunities surrounding its implementation (Kamga & Yazici). Finally, the potential intermodal role of HSR within the transportation network will be analyzed, considering its implications for sustainability and urban mobility (Kamga & Yazici; Vickerman).

In light of these discussions, this paper asserts that HSR represents a pivotal strategy for advancing sustainability in transportation systems. By leveraging HSR's capacity to reduce carbon emissions, enhance social equity, and stimulate economic development, policymakers can catalyze the transition towards more sustainable and inclusive urban transportation networks.

### **Introduction to High-Speed Rail**

HSR represents a significant advancement in transportation technology, offering a departure from conventional train systems by leveraging sophisticated vehicles and specialized tracks to sustain remarkably high speeds. While the notion of high-speed trains often conjures images of rapid movement, the underlying mechanics are far more intricate. Defined as trains capable of achieving speeds considerably higher than traditional counterparts, HSR embodies a complex amalgamation of engineering principles and design intricacies (Encyclopædia Britannica, 2024). Baig, Khan, and Baig (2016) elaborate on the technical aspects, emphasizing the importance of understanding the underlying mechanisms that enable such swift travel.

One key distinction lies in the types of tracks required to accommodate high-speed trains. Various track designs have been developed to withstand the stresses induced by the velocity of passing trains, ensuring both operational efficiency and passenger safety. Maglev systems, for instance, utilize magnetic levitation to propel trains without physical contact with the track, enabling speeds exceeding traditional rail systems. This innovative approach minimizes friction, allowing for unparalleled velocities while mitigating wear on the track (Baig et al., 2016).

Furthermore, the power requirements of high-speed trains necessitate advanced propulsion methods. In the case of maglev trains, a method called inductive power transfer (IPT) is used to send electricity to the train using electromagnetic fields to transfer power wirelessly, which allows the train to move more freely because it doesn't need to stay connected to power

cables on the tracks (Baig et al., 2016). Since there are no physical connections to wear out, it also means less maintenance is needed for the train system. Overhead wire contact systems offer another means of power transfer, utilizing long wires running parallel to the track to supply electricity to the train. These systems, though distinct in operation, share the common goal of powering high-speed trains reliably and sustainably (Baig et al., 2016).

Aerodynamics also plays a crucial role in optimizing high-speed rail performance. Streamlined train designs minimize aerodynamic drag, the resistance encountered by the vehicle as it moves through the air, thereby enhancing efficiency and reducing energy consumption. Engineers strive to create shapes that minimize resistance and turbulence, allowing trains to traverse at high speeds with minimal energy expenditure. By understanding and manipulating the flow field around trains, engineers can optimize designs to achieve maximum efficiency (Baig et al., 2016). Optimized efficiency of engineered trains can stimulate economic development through decreases in commute times and resource consumption.

Moreover, the economic implications of high-speed rail are substantial, extending beyond mere convenience to encompass job creation, economic growth, and environmental sustainability. Investment in HSR infrastructure stimulates employment opportunities and fosters economic development, while reducing congestion and dependence on fossil fuels (Baig et al., 2016). As populations grow and urbanization intensifies, HSR offers a viable solution to alleviate transportation burdens and enhance mobility for individuals and goods.

### **Environmental Benefits of High-Speed Rail**

HSR stands out as a pivotal contributor to environmentally sustainable transportation, offering substantial benefits in curbing carbon emissions and fostering green development. Amidst China's burgeoning HSR network expansion, Liu, Zhang, and Cao (2022) provide

insights into the ecological impacts of HSR deployment, assessing its influence on urban green development. Their findings, employing the SBM-DDF-SML (Slack Based Measure-Data Development Analysis-Super Efficiency Model) model and spatial difference-in-differences (SDID) methodology, underscore HSR's significant role in enhancing green total factor productivity (GTFP) in serviced cities, while also affecting neighboring areas. The SBM-DDF-SML model and SDID methodology are advanced statistical techniques used to analyze the impact of high-speed rail on green total factor productivity in different geographical areas. Green total factor productivity specifically evaluates the efficiency of resource use in relation to environmental outcomes. The analysis revealed that from 2006 to 2017, there was a noticeable growth trend in GTFP in both HSR-served and non-HSR-served cities; however, after the introduction of China's first HSR in 2008, HSR-served cities experienced a significantly larger increase in GTFP compared to their non-HSR counterparts (Liu et al., 2022). The study indicates that HSR-served cities became more efficient in using resources with positive environmental outcomes, highlighting the effectiveness of high-speed rail in promoting sustainable urban development.

The escalating environmental challenges stemming from rapid industrialization and urbanization necessitate urgent interventions to mitigate greenhouse gas emissions and environmental degradation. Governments worldwide have grappled with these issues, seeking pathways toward green growth models to harmonize economic development with environmental stewardship (Liu et al., 2022). In China, a central hub of global economic growth, the call for sustainable development is urgent, considering the significant environmental impact resulting from rapid economic progress. As economic prosperity burgeons, so do concerns regarding air

pollution, soil contamination, and water quality deterioration, underscoring the urgency of transitioning to green development paradigms (Liu et al., 2022).

Central to the discourse on green development is the concept of the Green Total Factor Productivity (GTFP), serving to quantify environmentally-conscious urban development (Liu et al., 2022). HSR emerges as a pivotal infrastructure component in this context, with its potential to reshape urban landscapes while concurrently curbing environmental degradation. Liu et al. (2022) uncover that the mechanisms through which HSR investments stimulate green innovation and foster sustainable urban ecosystems primarily involve the promotion of population clustering, reduction of commuting costs, facilitation of academic communication activities, and stimulation of innovation output among firms and society. Additionally, HSR encourages entrepreneurial vitality, which accelerates regional entrepreneurial enthusiasm, promotes new business opportunities, and drives forward-looking entrepreneurial thinking. These findings collectively highlight how HSR acts as a catalyst for green innovation and entrepreneurial activity, ultimately enhancing green total factor productivity (GTFP) in serviced cities and neighboring areas.

Moreover, HSR deployments catalyze green innovation ecosystems, fostering knowledge exchange, and talent mobility across urban centers. One example comes from China, where a study conducted using the number of self-employed people as entrepreneurs proved to show statistical significance in HSR improving entrepreneurship (Liu et al., 2022). The accessibility afforded by HSR corridors facilitates cross-regional collaborations, spurring innovation-driven economic growth and enhancing urban competitiveness (Liu et al., 2022). By streamlining transportation networks and reducing transaction costs, HSR investments stimulate research and

development activities, particularly in green technologies, thus amplifying the transformative potential of sustainable development initiatives (Liu et al., 2022).

### **Social and Economic Significance of Automobiles and Air Travel**

The social and economic significance of automobiles and air travel is deeply intertwined with cultural norms and economic factors, shaping mobility patterns, economic development, energy consumption, land use, and overall service quality. While high-speed rail (HSR) has emerged as a competitive alternative in transportation, particularly in countries like Japan, France, and Germany, its success has expanded globally, with notable achievements in China, Italy, Spain, and Korea. A study conducted by Sun, Zhang, and Wandelt (2017) found that HSR had a substantial impact on various facets of transportation, including mobility patterns, economic development, energy consumption, and service quality.

In regions like China, where HSR networks are extensive and construction costs relatively low, HSR has become the preferred mode of transportation for many passengers, particularly for medium-distance journeys where travel times are comparable to air travel but ticket prices are significantly lower (Sun et al., 2017). This shift in passenger demand from air to rail has implications for the aviation industry, leading to reductions in short-haul market share for airlines and influencing ticket prices and profitability (Sun et al., 2017).

Moreover, the competition and cooperation dynamics between air transport and HSR vary across regions, influenced by factors such as route structure, construction costs, and passenger preferences. While HSR networks continue to expand in countries like China, Japan, and Korea, they face different challenges and opportunities compared to their European counterparts, with variations in network density, construction costs, and profitability (Sun et al., 2017). While HSR has been economically profitable and has seen increases in popularity



amongst travelers in several Asian countries, other countries in Europe have seen low demand and economic incentives for effective utilization (Sun et al., 2017).

In terms of environmental and social welfare impacts, HSR often presents advantages over air travel, particularly in terms of CO<sub>2</sub> emissions reduction and overall environmental performance. Studies comparing the two modes of transportation have shown that HSR can offer significant environmental benefits, such as an 18% decrease in carbon emissions, noise, land use, and energy consumption (Strauss et al., 2021). However, it is important to note that the environmental benefits of HSR can vary depending on factors such as load factor, route structure, and integration with other modes of transportation, and it is important to take into consideration how to optimize these factors to mitigate further energy consumption (Sun et al., 2017). In the U.S., debates concerning how the construction of HSR in regards to environmental impact produce a hindrance to progressing development, paired with other institutional factors and public sentiments.

### **Challenges and Opportunities for HSR Implementation**

The challenges facing HSR implementation in the United States are multifaceted, encompassing technical, logistical, and environmental aspects (Chester & Ryerson, 2014). These challenges underscore the need for comprehensive strategies to address various complexities and ensure successful HSR integration into the transportation network.

Spatial incompatibility between different transportation modes, such as aviation, road networks, and HSR infrastructure, presents a significant hurdle (Chester & Ryerson, 2014). This spatial incongruity complicates environmental assessments and modeling of intermodal competition, highlighting the need for innovative approaches to ensure seamless integration and minimize environmental impacts. Accurate ridership forecasting is crucial for effective HSR

implementation and environmental assessments (Chester & Ryerson, 2014). Precise predictions enable comprehensive evaluation of HSR's environmental implications, emphasizing the importance of robust methodologies and data-driven approaches in planning and decision-making processes. The current environmental review process in the US tends to prioritize project-specific assessments over broader alternative evaluations, hindering informed decision-making regarding HSR (Chester & Ryerson, 2014). Overcoming this challenge requires revisiting regulatory frameworks to ensure comprehensive analysis and consideration of alternative modes, fostering a more holistic approach to HSR planning and implementation.

Future technological advancements in vehicle technologies and fuels present additional challenges for environmental assessments in the context of HSR (Chester & Ryerson, 2014). Addressing uncertainties surrounding vehicle technologies, fuel sources, and market regulations is essential for accurately assessing HSR's environmental impacts and informing sustainable transportation policies. Institutional and cultural barriers, including individualism, anti-statism, populism, and egalitarianism, pose significant challenges to HSR implementation in the United States (Chen, 2012). Recognizing and mitigating these barriers is crucial for fostering broader societal acceptance of HSR as a sustainable transportation solution, emphasizing the need for collaborative efforts and stakeholder engagement in HSR planning and decision-making processes.

### **Integrating High-Speed Rail With Current Transportation & Technology**

The integration of high-speed rail (HSR) within existing transportation systems presents both challenges and opportunities, shaping urban mobility and connectivity. Understanding these dynamics is crucial for effective HSR implementation (Chester & Ryerson, 2014). Integrating HSR within existing transportation systems is crucial for enhancing urban mobility and

connectivity, which are key aspects of sustainable urban development. This understanding underscores the importance of addressing challenges and leveraging opportunities in HSR integration.

HSR's proximity to urban centers offers quicker transit compared to air transport, despite potentially covering longer distances. This advantage underscores HSR's role in enhancing urban connectivity and accessibility (Xia & Zhang, 2017). The accessibility of HSR stations near urban centers not only reduces travel time but also enhances the overall connectivity of cities, contributing to improved accessibility for residents and businesses.

Furthermore, ensuring the safety and efficiency of HSR projects requires robust wireless communication systems. As train speeds increase, systems like the European train control system (ETCS) and dedicated mobile communication systems become essential for reliable train control (Ai et al., 2014). With the increasing speeds of HSR trains, the reliability of wireless communication systems becomes paramount for ensuring passenger safety and operational efficiency. Effective communication systems enable precise train control, reducing the risk of accidents and delays.

However, challenges persist in developing wireless communication technologies tailored to HSR environments. Special propagation scenarios, high speeds exceeding 300 km/h, and harsh electromagnetic conditions necessitate effective channel modeling and frequency band selection (Ai et al., 2014). Overcoming these challenges requires innovative approaches to wireless communication technology, considering the unique characteristics of HSR environments. Effective channel modeling and frequency band selection are essential for ensuring uninterrupted communication between trains and ground control centers, thereby enhancing the safety and reliability of HSR operations.

Empirical studies highlight consumer preferences for HSR over air travel on certain routes, indicating HSR's competitiveness in specific markets. Shorter air-rail connecting times increase consumer surplus and benefit both urban mobility and operator profitability (Xia & Zhang, 2017). Understanding consumer preferences is crucial for shaping transportation policies and investment decisions. The preference for HSR over air travel on certain routes suggests the potential for HSR to capture market share and improve overall transportation efficiency. Additionally, shorter air-rail connecting times not only enhance consumer satisfaction but also contribute to increased revenue for operators, ultimately benefiting urban mobility and economic development.

The interplay between air and HSR transport impacts social welfare and operator profits. Optimizing air-rail integration can enhance overall welfare through competition or cooperation between modes, depending on factors like hub airport capacity (Xia & Zhang, 2017). Balancing competition and cooperation between air and HSR transport is essential for maximizing the social and economic benefits of both modes. Effective integration strategies can improve overall welfare by increasing transportation efficiency, reducing congestion, and enhancing passenger experience.

Addressing these challenges requires developing robust methodologies for assessing environmental impacts and integrating HSR within existing transportation systems effectively. While challenges persist, HSR integration offers significant opportunities for enhancing urban mobility, improving connectivity, and promoting sustainable transportation solutions. Developing robust methodologies for environmental assessment and effective integration of HSR within existing transportation systems are essential steps towards realizing the full potential of HSR as a sustainable transportation solution (Chester & Ryerson, 2014). Overcoming challenges

in HSR integration can lead to significant benefits in terms of enhanced urban mobility, improved connectivity, and reduced environmental impact, ultimately contributing to the development of more sustainable and livable cities.

### **Conclusion: Advancing Sustainability Through High-Speed Rail**

HSR stands as a beacon of hope in the realm of sustainable transportation, offering a compelling solution to the urgent challenges facing modern mobility. In the face of mounting environmental degradation, congestion, and social inequities, HSR emerges as a transformative force, driven by its remarkable speed, efficiency, and environmental benefits.

By reducing carbon emissions, enhancing social equity, and stimulating economic development, HSR offers a pathway towards more sustainable and inclusive transportation systems. Its integration within existing transportation networks presents opportunities to enhance urban connectivity and accessibility, paving the way for greener, more efficient cities.

However, realizing the full potential of HSR requires coordinated efforts and innovative approaches. Robust methodologies for environmental assessment, effective integration within transportation networks, and mitigation of institutional and cultural barriers are essential steps towards harnessing the transformative power of HSR.

In conclusion, HSR represents more than just a mode of transportation; it embodies a vision for a greener, more sustainable future. Through collaborative efforts and strategic planning, HSR has the potential to shape the cities of tomorrow, offering a brighter and more sustainable path forward for transportation worldwide.

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