Optimizing Sustainability in High-Speed Rail Rolling Stock through CFRP Material Substitution

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Abstract. This research investigates the environmental and operational advantages of replacing traditional materials in high-speed rail (HSR) rolling stock components with advanced composite materials. By substituting key parts—such as the roof, door, car body, brake control unit, braking rheostat, and bogie transom—with glass-filled epoxy, polyester, and nylon, the study achieves a significant reduction in rolling stock weight by 24.61%. This weight reduction contributes to lower energy consumption and reduced CO_2 emissions. Additionally, the recyclability and recoverability rates of these composite materials show marked improvements, reaching 73.9% and 78.9%, respectively, compared to 61.4% and 73.1% in the conventional model. The findings demonstrate that integrating composite materials can enhance the sustainability and efficiency of HSR systems by minimizing landfill waste and operational emissions. This study provides a foundational approach to using lightweight, recyclable materials in rail transportation, with promising implications for future sustainable developments in the industry.

1 Introduction

The expansion of railway systems globally has established rail transport as a cornerstone of public infrastructure, positively impacting human life by providing efficient, reliable, and low-emission transportation options [1]. However, this growth has also increased CO_2 emissions, contributing to global climate change. High-speed rail (HSR) systems, known for their lower emissions compared to other transportation modes, are continuously optimized to further reduce their environmental footprint [2]. One promising approach is the replacement of traditional materials with composite materials, which can significantly reduce the weight of rolling stocks and improve recyclability and recoverability [3-4]. This study explores the use of glass-filled epoxy, polyester, and nylon to replace key components in HSR rolling stocks, aiming to enhance sustainability and efficiency.

1.1 Carbon Fiber Reinforced Polymer Material

The focus of this research is on substituting six primary components in HSR rolling stocks—roof, door, car body, brake control unit, braking rheostat, and bogie transom—with three types of composite materials: glass-filled epoxy, glass-filled polyester, and glass-filled nylon. These materials were chosen for their high stiffness, strength, and low density, which are crucial for reducing the overall weight of the rolling stock and improving fuel efficiency [5-6].

Carbon Fiber Reinforced Polymer (CFRP) composites have gained significant attention in the rolling stock industry due to their exceptional strength-to-weight ratio and corrosion resistance properties. These advanced materials consist of carbon fibers embedded in a polymer matrix, offering a combination of high stiffness, fatigue resistance, and low density [7]. In rolling stock applications, CFRP has been successfully utilized to reduce vehicle weight, thereby improving energy efficiency and operational performance.

The implementation of CFRP in rolling stock design has led to notable improvements in various components. For instance, CFRP has been employed in the construction of lightweight car bodies, bogie frames, and interior panels [8]. This weight reduction not only enhances fuel efficiency but also allows for increased payload capacity. Additionally, the use of CFRP in structural elements has demonstrated improved crashworthiness and impact resistance compared to traditional metallic materials [9].

Despite the advantages, challenges remain in the widespread adoption of CFRP in rolling stock, including higher initial costs and complex manufacturing processes. However, ongoing research and development efforts are focused on addressing these limitations, paving the way for broader implementation in future railway vehicles.

1.2 Beneficial of local content's improvement

The implementation of CFRP in rolling stock offers an opportunity to improve local content in the railway industry. As railway's industries aim to enhance domestic manufacturing and reduce imports, CFRP technologies can play a crucial role [7]. This process involves developing local capacity for CFRP production, from raw materials to final products.

Key elements include technology transfer through international collaboration, investment in infrastructure for carbon fibre and composite manufacturing, and workforce development. Supply chain development and encouraging local R&D initiatives are also essential [8].

This approach boosts the domestic economy and allows customization of CFRP solutions for local needs. However, challenges like high initial costs and quality control must be addressed. Government and industry collaboration is necessary to create policies and incentives facilitating this transition towards increased local CFRP production in the rolling stock sector [9-10]

2 Methodology

This study focuses on evaluating the replacement of traditional materials with composites in HSR rolling stock. It begins with identifying suitable HSR components for material substitution, including the roof, doors, car body, brake control unit, braking rheostat, and bogie transom. The process then involves calculating the new total mass of the rolling stock after replacing these components with composite materials such as glass-filled epoxy, polyester, and nylon.

This study employs a comprehensive approach to evaluate the replacement of traditional materials with composites in HSR rolling stock. The methodology consists of four key steps:

2.1 Component Selection

The research begins by identifying suitable HSR components for material substitution. Six key parts are selected. These components are chosen based on their significant contribution to the overall weight of the rolling stock and the potential benefits of using lighter materials as shown in Figure 1.

2.2 Material Replacement

Three types of composite materials are considered for replacement: glass-filled epoxy, glass-filled polyester, and glass-filled nylon. These materials are selected for their high stiffness, strength, and low density, which are crucial for reducing the overall weight of the rolling stock.

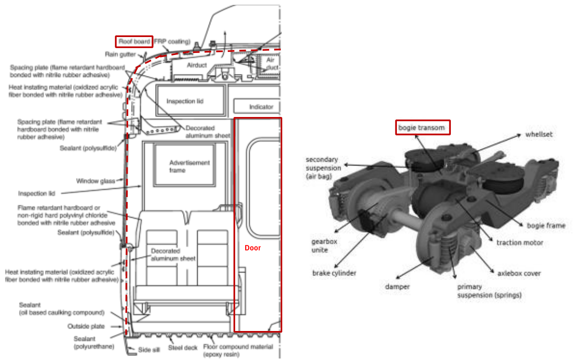

Fig. 1 An overview on component of (a) rolling stock (adapted from Dinmohammadi et al., 2016) [11]; (b) bogie part (adapted from railsystem, n.a.) [12].

2.3 Mass Calculation

The new total mass of the rolling stock is calculated after replacing the selected components with composite materials. This calculation considers the density and volume of the chosen composite materials. This step is critical for determining the extent of weight reduction achieved through the substitution.

$$M = \rho \times V \qquad (1)$$

Where; M = Mass of component (m^3); ρ = Density (kg/m^3); V= Volume (kg)

$$\gamma i = \sum m_j \cdot MRF_{j.} \qquad (2)$$

$$\%R_{cyc} = \frac{\sum \gamma i}{m_v} \times 100\% \qquad (3)$$

$$\%R_{cov} = R_{cyc(\%)} + \left(\frac{\sum m_j \cdot ERF_j \times}{m_v} 100\%\right) \qquad (4)$$

γi = The total mass that can be recycled; m_j = The mass of each individual component within the vehicle; M_v: The total mass of the entire vehicle or rolling stock; MRF = The percentage factor representing how much of a component's mass can be recovered through recycling; ERF = The percentage factor representing the amount of a component's mass that can be recovered as energy.

2.4 Environmental Impact Assessment

A key aspect of the methodology is evaluating the environmental impact of the material replacement. This involves a calculating the recyclability (%R_{cyc}) and recoverability (%R_{cov}) rates of the new composite materials compared to the traditional materials used in the original HSR model. And, Assessing the impact of weight reduction on fuel consumption and CO_2 emissions during HSR operation [13].

As shown in Fig. 2, The sharp increase in aluminum recycling reflects a broader shift within industries toward higher recyclability rates and environmental sustainability. Just as the aluminum industry has reduced its reliance on primary production by enhancing recycling practices, the proposed material replacement in high-speed rail (HSR) systems aims to improve both %R_{cyc} and %R_{cov} rates.

By substituting traditional materials in HSR rolling stock with advanced composites like glass-filled epoxy, polyester, and nylon, the study seeks to achieve outcomes similar to those observed in the aluminum industry. The increased use of recyclable materials can lead to less reliance on new raw materials, lowering the environmental impact by reducing waste and energy consumption. Additionally, weight reduction due to the use of lighter composite materials directly affects fuel consumption and CO_2 emissions. Lower weight means less energy is required to operate HSR, resulting in reduced fuel costs and emissions, as seen with increased recycling's effect in the aluminum industry.

These parallel highlights the importance of sustainable material selection and enhanced recyclability for achieving environmental goals in HSR systems, like the strategies used in aluminum production to reduce carbon footprints and improve lifecycle sustainability.

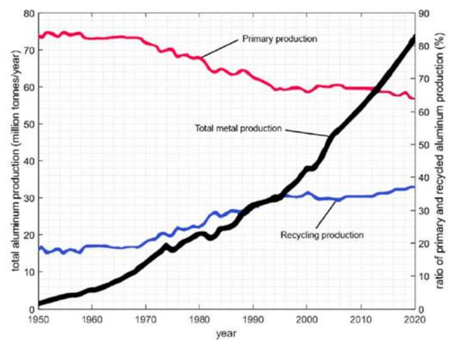

Fig. 2 The proportion of recycled materials in aluminum production (Rungskunroch et.al, 2019) [14].

3 Result

The study results reveal that replacing six key components of the HSR rolling stock with composite materials significantly reduces the overall weight. The original model's weight of 265,000 kg was reduced to 201,124.69 kg with the introduction of glass-filled epoxy, glass-filled polyester, and glass-filled nylon. This weight reduction of 24.61% decreases the energy required to operate the HSR, leading to lower fuel consumption and CO_2 emissions.

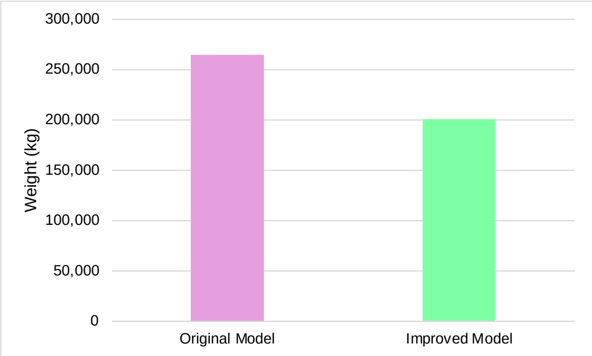

Fig. 3 The comparison on total weight of original and improved model

Furthermore, the overall $\%R_{cyc}$ improved from 61.4% to 73.1%, and the $\%R_{cov}$ increased from 73.9% to 78.9%. These improvements in $\%R_{cyc}$ and $\%R_{cov}$ result in a significant decrease in landfill waste, from 88,201 kg in the original model to 14,420 kg in the improved model. The use of CFRP materials in the rolling stock components enhances environmental sustainability by reducing both landfill waste and emissions

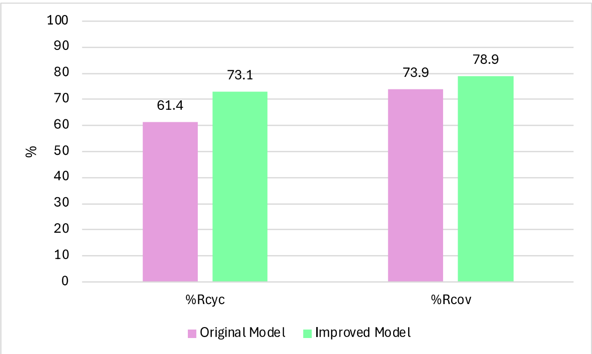

Fig. 4 The comparison $\%R_{cyc}$ and $\%R_{cov}$ of original and improved model

4 Parametric Study

The parametric study focuses on predicting future recycling rates for mixed aluminium and steel, considering advancements in recycling technologies. The study projects that by 2039, the recycling rate for mixed aluminium and steel will reach 96%, significantly reducing landfill waste. The predictive model shows that by 2039, leftover waste will decrease to 13,094.98 kg, with 270,799.02 kg of recyclable components. This indicates that technological advancements in recycling processes can drastically decrease environmental impacts, supporting the sustainability of HSR systems

5 Discussion

The findings underscore the significant advantages of replacing traditional materials with composite materials in HSR rolling stocks. The weight reduction leads to lower fuel consumption, directly translating to reduced CO_2 emissions. The improved $\%R_{cyc}$ and $\%R_{cov}$ of composite materials contribute to long-term environmental sustainability by minimizing landfill waste and enhancing resource recovery. These results align with previous research that highlights the benefits of lightweight materials in transportation, reducing greenhouse gas emissions and improving fuel efficiency.

The improved model demonstrates the feasibility and desirability of using CFRP composite materials in HSR systems. While the current model is ready for implementation, the predictive model for 2039 requires further technological advancements to support enhanced recycling processes. Nevertheless, the immediate benefits of the improved model are clear, providing a viable path forward for sustainable rail transport.

6 Conclusion

The implementation of CFRP composite materials in HSR rolling stock components demonstrates significant potential for enhancing environmental sustainability. This study's findings indicate that the substitution of traditional materials with CFRP composites yields a substantial 24.61% reduction in overall vehicle mass. This weight reduction correspondingly results in decreased fuel consumption and lower CO_2 emissions during operational phases.

Furthermore, the investigation reveals improved $\%R_{cyc}$ and $\%R_{cov}$ for CFRP composites compared to conventional materials. These enhanced rates contribute to a marked reduction in landfill waste, aligning with circular economy principles and waste management objectives in the transportation sector.

The observed benefits in weight reduction, operational efficiency, and end-of-life material management collectively underscore the feasibility and advantages of integrating CFRP composite materials in future HSR rolling stock designs. These results suggest that the adoption of such advanced materials can significantly contribute to improved efficiency and sustainability in rail transportation systems.

These outcomes provide empirical support for the potential of CFRP composites to address key environmental challenges in the HSR industry, offering a promising avenue for future research and development in sustainable railway technologies.

References

1. UIC (International Union of Railways). (2015). Railway Handbook 2015: Energy Consumption and CO_2 Emissions.

2. Yeh, S., Mishra, G. S., Fulton, L., Kyle, P., McCollum, D. L., Miller, J., & Weyant, J. (2017). Detailed assessment of global transport-energy models' structures and projections. Transportation Research Part D: Transport and Environment, 55, 294-309.
3. Kaewunruen, S., Rungskunroch, P., & Jennings, D. (2019). A through-life evaluation of end-of-life rolling stocks considering asset recycling, energy recovering, and financial benefit. Journal of Cleaner Production, 212, 1008-1024.
4. Damgaard, A., Larsen, A. W., & Christensen, T. H. (2009). Recycling of metals: accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27(8), 773-780.
5. Greem, J. A. S. (2007). Aluminium Recycling and Processing for Energy Conservation and Sustainability. ASM International.
6. IEA (International Energy Agency). (2022). Rail. https://www.iea.org/reports/rail
7. This report provides up-to-date information on the rail sector's energy consumption and emissions.
8. Soutis, C. (2005). Carbon fiber reinforced plastics in aircraft construction. Materials Science and Engineering: A, 412(1-2), 171-176.
9. Matsika, E., Ricci, S., Mortimer, P., Georgiev, N., & O'Neill, C. (2013). Rail vehicles, environment, safety and security. Research in Transportation Economics, 41(1), 43-58.
10. Carruthers, J. J., Kettle, A. P., & Robinson, A. M. (2011). Energy absorption capability and crashworthiness of composite material structures: A review. Applied Mechanics Reviews, 61(1), 010802.
11. Dinmohammadi, F., Alkali, B., Shafiee, M. *et al.* Risk Evaluation of Railway Rolling Stock Failures Using FMECA Technique: A Case Study of Passenger Door System. *Urban Rail Transit* **2**, 128–145 (2016). https://doi.org/10.1007/s40864-016-0043-z
12. Railsystem (n.a.) Available at : https://railsystem.net/bogie/ (Accessed on 15 October 2024)
13. Andersen, P. H., & Greve, H. R. (2021). Local content requirements and the global rail industry: Navigating institutional voids and capturing value. Journal of World Business, 56(3), 101188.
14. Rungskunroch P, Kaewunruen S and Shen Z-J (2019) An Improvement on the End-of-Life of High-Speed Rail Rolling Stocks Considering CFRP Composite Material Replacement. *Front. Built Environ.* 5:89. doi: 10.3389/fbuil.2019.00089