Carbon Emission Characteristics of Railways

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Rail transportation plays a crucial role in reducing carbon emissions from the transportation system, making a significant contribution to environmental impact mitigation due to the efficiency of passenger and freight rail transportation. Estimates of greenhouse gas (GHG) emissions impacts into the atmosphere are intrinsically linked to the modernization of transportation system, due this sector still heavily relies on fossil fuels, such as gasoline and diesel. In the context of studying GHG emissions and their life cycle, it is common to assess different alternatives to identify the most sustainable options. For example, when comparing different transportation systems, one can analyze not only the direct emissions from vehicles but also emissions associated with the manufacturing, maintenance, and operation of infrastructure such as roads, rails, or airports

Keywords: railway ; sustainability ; GHG emission ; climate change

1. Introduction

The increase in concentrations of greenhouse gas (GHG) emissions in the atmosphere has led to an amplified greenhouse effect, resulting in higher average temperatures worldwide. This global warming causes a range of adverse impacts on various aspects of the biosphere, from natural ecosystems to human activities [1].

Climate change represents one of the most pressing and complex challenges that humanity faces in the 21st century. It reflects significant changes in global climate patterns over time, primarily driven by human activity and its emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [2]. International cooperation plays a crucial role in addressing climate change, as evidenced by the Paris Agreement, a global milestone aimed at limiting global warming well below 2 °C compared to pre-industrial levels. Individual efforts, governmental actions, and corporate commitments are also essential to tackle this challenge [3].

Europe, for instance, is significantly impacted by climate change, presenting a series of environmental, social, and economic challenges for the region. These impacts are observed in various areas and have profound implications for European countries and the continent as a whole [4][5]. To address these challenges, the European Union and its member states are implementing policies and actions to mitigate and achieve climate neutral by 2050, through green technology, sustainable industry and clean transport. Investments in sustainable technologies, promotion of energy efficiency, protection of natural ecosystems, and public awareness are key strategies to reduce greenhouse gas emissions [6][7]. This involves decarbonization of industrial activities by transitioning to renewable energy sources, the electrification of vehicle (including trains, buses, planes, boats and cars) and investing in fleets powered by other alternative energy sources, such as hydrogen, efuels or biofuels. Furthermore, adaptation is equally crucial, involving the implementation of strategies to address ongoing impacts and the development of resilient infrastructures [8].

Europe plays an active role on the international stage, working together with other countries to build a more sustainable and resilient future in the face of climate change [9][10]. However, it's important to emphasize that climate change knows no borders, and international cooperation is essential to address this global challenge. In light of this panorama, climate change mitigation has become a global priority.

Furthermore, climate change disproportionately affects vulnerable populations, such as low-income communities, indigenous peoples, and densely populated coastal regions. Lack of access to resources, adequate infrastructure, and early warning systems increases their susceptibility to extreme weather events, exacerbating existing inequalities and creating new socio-economic challenges. This reality underscores the urgency of addressing climate change not only as an environmental issue but also as a matter of social justice and human rights [11][12]. Awareness, education, and cooperation are essential to confront this threat and ensure a healthy and habitable planet for present and future generations [12][13][14].

Therefore, the study of greenhouse gas (GHG) emissions and their life cycle is a crucial research area for understanding the environmental impact of human activities and developing strategies for climate change mitigation [13]. The life cycle approach is a valuable tool for analyzing environmental burdens and impacts of GHG emissions across all stages of a process, product, or system, from raw material extraction to final disposal. This includes production, transportation, use, and disposal of goods and services. Life cycle assessment (LCA) involves collecting detailed data on material flows, energy, and emissions at each stage, enabling a comprehensive analysis of environmental impacts [15][16].

Estimates of GHG emissions impacts into the atmosphere are intrinsically linked to the modernization of transportation system, due this sector still heavily relies on fossil fuels, such as gasoline and diesel, currently accounting for over 20% of global CO_2 emissions. The impact of GHG from the transportation system is complex and encompasses a variety of transportation modes and related practices [17][18]. Studies show that factors such as population growth and concentration, economic growth, technological development, and motorization rates increase energy intensity and CO_2 emissions. According to Tang and Jiang, the effects of energy intensity, population urbanization, industry scale, and energy structure collectively exert negative driving influences because propelling the augmentation of carbon emissions [19].

In the context of studying GHG emissions and their life cycle, it is common to assess different alternatives to identify the most sustainable options. For example, when comparing different transportation systems, one can analyze not only the direct emissions from vehicles but also emissions associated with the manufacturing, maintenance, and operation of infrastructure such as roads, rails, or airports [19]. Furthermore, life cycle analysis can highlight opportunities to reduce emissions at different stages of the cycle. This might involve improving energy efficiency in vehicle production, using more sustainable materials, promoting public transportation, expanding bike lane networks, and implementing policies that encourage the adoption of the mode/service with the lowest carbon footprint [20].

In this context, railways transportation has the potential to assume a central role in long-term transport sector decarbonization and provide huge opportunities with the modernizing of infrastructure, contributing to the reduction of GHG emissions and the development of more efficient and environmentally responsible transportation systems [19]. The life cycle analysis in the railway context is an approach that enables a complete understanding of the common environmental impact hotspots of railway operations, from the design and construction of infrastructures to the operation and maintenance of railway systems. This comprehensive methodology is essential for accurately and holistically assessing emissions associated with rail transportation and identifying mitigation opportunities [21][22].

Greenhouse gas emissions from the transportation system, including railways, pose one of the major challenges in addressing climate change. Furthermore, this approach allows for identifying critical emission points throughout the life cycle where interventions can be made to formulating policies for low-carbon development and to reduce overall emissions. This might involve adopting cleaner technologies, improving energy efficiency, changing consumption patterns, or implementing more sustainable practices [23][24]. The adoption of cleaner technologies, promotion of sustainable transportation alternatives, and smart urban planning are essential to mitigate the environmental impacts of the transportation sector and contribute to a more sustainable future [25].

2. Carbon Emission Characteristics of Railways

As carbon emission characteristics in the railway context are of great importance when considering the environmental footprint of this mode of transportation. Carbon emissions, primarily in the form of GHG, play a significant role in global climate change. Railways, as a mode of transportation, possess distinct characteristics that influence their carbon emissions and contribution to global warming [26].

One of the distinctive features of railways is their energy efficiency compared to other modes of transportation, such as roads and airplanes. Generally, rail transportation is considered one of the most efficient and environmentally friendly modes in terms of carbon emissions. Trains have a high capacity for carrying freight and passengers, resulting in relatively higher energy efficiency per unit of cargo or passenger transported [11][27]. Furthermore, electrification of railways, when electricity is sourced from renewable sources, can further reduce local carbon emissions. This leads to railway transportation emitting less compared to other modes [9].

Road transportation, which includes cars, trucks, and buses, generally has a higher carbon footprint compared to the railway system. This is partly due to the lower energy efficiency of these vehicles, especially when carrying smaller loads or fewer passengers [28]. Internal combustion engines commonly used in road vehicles are less efficient in terms of energy conversion while in motion, resulting in higher fuel consumption and consequently higher GHG emissions [29]. Moreover, a study on the impact of cargo modal transfer policy on carbon emissions in China concluded that road transportation is the most polluting mode among various transportation modes, while rail transportation has lower carbon emissions [30].

However, buses don't always emit more GHGs than trains. The case of the Sheppard subway line in Toronto, Canada, highlights the complexity of analyzing greenhouse gas emissions in transportation systems and how results can vary over time. In this specific example, the subway line initially produced more GHGs per passenger-kilometer than the buses it replaced during the first six years of operation. However, after this period, the carbon reduction benefits of the subway line began to become more evident [31].

This case underscores the importance of considering the evolution over time when assessing the environmental benefits of transportation projects. While the initial impact may not be immediately positive, the potential for significant reductions in GHG emissions can materialize as the system matures and becomes more efficient. This also highlights the need for a comprehensive and long-term approach when planning and evaluating transportation projects with the goal of mitigating climate change and reducing carbon emissions.

If transportation, on the other hand, is known to have a significantly higher carbon footprint compared to rail and road systems. Airplanes consume large amounts of fuel during flight, resulting in substantial GHG emissions per passenger or cargo transported. Additionally, GHG emissions from aviation occur at higher altitudes, which can have an amplified impact on the climate. Although there have been advances in improving the efficiency of jet engines and the adoption of biofuels, air transport is still considered one of the most polluting modes in terms of carbon emissions [25][32][33][34].

Comparing carbon emissions between rail, road, and air systems underscores the importance of energy efficiency and the type of fuel used. The railway system stands out for being more efficient and often cleaner due to electrification. The road system generally occupies an intermediate position in terms of emissions, while the air system is recognized for its relatively high emissions. This comparison emphasizes the need to consider environmental sustainability when choosing a mode of transportation and highlights the importance of policies and innovations aimed at reducing GHG emissions across all modes of transportation [9]. Although railway systems are generally considered a more sustainable option in terms of carbon emissions compared to other modes of transportation, it is crucial to acknowledge that emissions may still occur, regardless of the type of energy used.

The electrification of railways in many regions contributes to carbon emission reduction. Electric trains directly eliminate emissions from the combustion of fossil fuels, making them a cleaner option in terms of local emissions. However, the carbon footprint of electrification depends on the energy mix used to generate electricity. If electricity comes from renewable sources, carbon emissions associated with railway operation can be further reduced [35][36].

The study analyzing the four typical urban railway lines (lines 6, 9, 10, and 15 of the subway) in Beijing in 2014 yielded important results regarding carbon emission reduction and the influence of various factors in this context. The results demonstrated the complex interconnection between urban rail transit, carbon emissions, and specific factors affecting these emissions [37].

The study showed that urban railway lines had a positive impact on carbon emission reduction in Beijing. This suggests that the implementation of these lines contributed to a more sustainable environment and the mitigation of greenhouse gas emissions. Carbon emissions from urban rail transit were strongly correlated with the carbon emission factor of the electricity used to power the system. This underscores the importance of the energy source behind rail transportation, with electrification and the use of clean energy sources being crucial to maximize environmental benefits [37].

The study also identified a correlation between carbon emissions and the proportion of passenger trips using modes of transportation prior to the opening of urban railway lines. This suggests that passenger adoption and switching to rail transportation had a direct impact on emissions reduction. The sensitivity analysis conducted in the study helped identify which factors significantly influenced carbon emissions. This is crucial to guide future planning decisions and public policies, aiming to optimize the environmental efficiency of urban railway lines [37].

Collectively, these findings highlight the importance of urban railway transportation as a more sustainable alternative to previous modes of transportation, contributing to carbon emission reduction in urban areas. Furthermore, they underscore the need for integrated approaches that consider not only the railway system itself but also influencing factors such as electricity sources and passenger behavior. This can inform transportation and energy policies aimed at continuous reduction of greenhouse gas emissions in urban areas.

An investigation in China identified railway electrification as a key means to reduce carbon emissions and optimize the transportation energy structure in the country. The results indicated that railway electrification using the current energy generation mix could reduce carbon emissions by 8.9%. However, utilizing a generation mix similar to that of the United Kingdom could help achieve a maximum reduction in carbon emissions of 65.4% [38]

A fundamental aspect highlighted by the research was the role of the energy generation mix in determining the effectiveness of railway electrification in reducing carbon emissions. The composition of energy sources used for electricity generation plays a crucial role, as cleaner sources such as renewables result in lower emissions associated with the operation of electric trains. The study demonstrated that adopting an energy generation mix similar to that of the United Kingdom, which has a substantial proportion of renewable energy in its energy mix, could lead to a much more significant reduction in carbon emissions in the Chinese railway system [38].

The importance of considering not only the electrification technology itself but also the origin of the electricity used to power railway systems is underscored. It also demonstrates the potential for international cooperation, as experiences and best practices from other countries can be leveraged to maximize the benefits of railway electrification in terms of carbon emission reduction. In summary, the research highlights railway electrification as a promising strategy to achieve emission reduction goals and optimize the energy structure in transportation systems, with positive implications for the environment and the global climate [38].

Railway electrification is recognized as a crucial strategy for making transportation systems more sustainable and with a lower carbon footprint. By replacing diesel locomotives with electric trains powered by renewable or cleaner energy sources, it’s possible to significantly reduce greenhouse gas emissions. This shift not only contributes to climate change mitigation but also improves air quality and reduces noise pollution in urban areas near railway lines [39].

It’s worth noting that carbon emissions are also related to operational practices and proper maintenance of tracks and trains [40][41][42]. Improvements in fleet management, regular maintenance, and route optimization can result in enhanced efficiency, which in turn can reduce carbon emissions. Furthermore, challenges related to infrastructure, network modernization, and expansion can also influence carbon emissions in different railway systems.

Carbon emissions in the railway sector are influenced not only by the energy sources used to power the trains but are also intrinsically linked to operational practices and proper maintenance of railway infrastructure and trains. The efficiency and sustainability of the railway system depend on a combination of factors, ranging from daily operations management to preventive maintenance strategies [26][43].

Operational practices play a pivotal role in determining carbon emissions. For instance, optimizing train scheduling and operations can result in lower energy consumption and, therefore, reduced emissions. The adoption of regenerative braking strategies, which capture and reuse part of the kinetic energy during train deceleration, can contribute to energy efficiency and emission reduction [44].

Moreover, proper maintenance of railway tracks and trains is crucial to minimize energy losses and ensure the efficient operation of the system. Well-maintained tracks reduce friction and allow smoother operation, which in turn reduces energy consumption. Similarly, regular maintenance of trains, including component cleaning and lubrication, ensures they operate efficiently, avoiding energy waste and unnecessary emissions [45][46][47][48].

Furthermore, innovative technologies such as more efficient propulsion systems and lightweight materials also play a role in reducing carbon emissions in the railway sector. Continuous research and development in these areas can contribute to improving energy efficiency and reducing emissions associated with railway operation [49].

The carbon emission characteristics of railways are shaped by their energy efficiency, electrification, and operational practices. While it offers advantages in terms of carbon emission reduction compared to other modes of transportation, it’s essential to consider the energy source and implement sustainable practices to maximize its environmental benefits. Understanding these characteristics is crucial for guiding efforts in carbon emission mitigation in the railway sector and contributing to the sustainability of the transportation system as a whole [10].

In another recent study, an estimation of carbon emissions generated by the daily operation of the metro system was conducted. The results obtained from this analysis allowed for the calculation of carbon emissions per kilometer traveled or per passenger trip. This approach provided a solid theoretical basis for the government to consider implementing policies such as carbon taxes for citizens and the creation of a carbon offset mechanism [50].

By determining the carbon emissions associated with the day-to-day operation of the metro system, this study contributed to understanding the specific contributions of this mode of transportation to greenhouse gas emissions. Quantifying emissions per kilometer or per passenger trip offered valuable information to underpin environmental and economic policy formulation [50].

Particularly, the study results served as a foundation for considering measures such as carbon taxes. This strategy aims to incentivize carbon emission reduction by imposing a tax on greenhouse gas emissions. By establishing such a tax, the government seeks not only to promote environmental awareness but also to create a financial incentive for adopting low-emission alternatives, such as the use of public transportation such as the metro, over more polluting modes [50].

Furthermore, the study paved the way for the implementation of a carbon offset mechanism. This refers to an approach in which individuals or organizations can invest in carbon mitigation projects, such as reforestation or clean technologies, to offset their own carbon emissions. This approach plays a significant role in combating climate change by encouraging actions that result in the neutralization or net reduction of greenhouse gas emissions [50].

The study conducted by Yu [50] played a pivotal role in providing a solid theoretical foundation for policy formulation such as carbon taxes and the implementation of a carbon offset mechanism. These strategies are crucial for promoting environmental awareness, encouraging the adoption of sustainable modes of transportation, and contributing to the mitigation of greenhouse gas emissions.

In summary, railways stand out as a mode of transportation with favorable carbon emission characteristics due to their energy efficiency, electrification options, and potential for ongoing emissions reduction through sustainable operational practices. These aspects make railways an attractive alternative for mitigating GHG emissions in the transportation sector and contributing to the pursuit of more sustainable solutions in addressing climate change.

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