Greenhouse Gas Emissions in Railways: Systematic Review of Research Progress

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Abstract: 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. Accurate assessment of carbon emissions resulting from rail transit is essential to quantify the positive impact of this mode of transportation on overall urban transport emission reduction. Given that measuring carbon emissions throughout the lifecycle of rail transportation involves a wide array of factors, adopting a systematic framework for analyzing these aspects is crucial. This study conducts a comprehensive review of existing research related to carbon emissions in rail transportation and its mitigation. Initially, the distinct characteristics of carbon emissions associated with rail transportation are identified, along with the complexity involved in accurately measuring these emissions. Subsequently, a comparison and analysis are conducted regarding various models for measuring carbon emissions in rail transportation. Finally, the study examines some greenhouse gas emission measurement research within the railway system. Redirecting research efforts toward measuring carbon emissions in the rail transportation system is essential to help the development of robust and effective public policies. This measure will play a crucial role in emission reduction, climate change mitigation, and the promotion of more sustainable transportation. Furthermore, the identified results propose which LCA methodology offers a valuable framework improving the quality of railway transportation emissions for future generations.

Keywords: railway; sustainability; GHG emission; LCA; 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 [12–14].

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].

In this context, this research provides a comprehensive approach to the study of investigation focusing on the analysis and measurement of greenhouse gas emissions in rail transportation. By doing so, it assists researchers in gaining a thorough understanding of the current state of research in this area and the persistent issues. Furthermore, it seeks to provide guidelines and recommendations for further in-depth investigation in this field in the future. Additionally, this research aims to address the following questions regarding studies of greenhouse gas emissions in the global railway system:

Q1. What are the carbon emission characteristics of railways?

Q2. What bibliographic trends exist in relation to studies of greenhouse gas emissions in railway systems?

Q3. What calculation models are used in research on carbon emissions from rail transportation?

Q4. What are the complexities and limitations of measuring carbon emissions from railway system?

Q5. What research trends exist regarding the mitigation of greenhouse gas emissions in the railway system?

2. Materials and Methods

This article proposes a systematic literature review focused on the analysis and measurement of greenhouse gas emissions in the context of railway transportation. The scope of this review primarily encompasses life cycle assessment (LCA) methods published between the years 2010 and 2023. A systematic review is defined as a critical synthesis of research evidence aimed at identifying, selecting, and synthesizing all published research on a specific topic or issue [11,17,26–29].The execution of this review follows a formal and rigorous methodological approach to achieve its objectives.

The systematic literature review process comprises three phases: Planning, Implementation, and Reporting. At the outset of this work, research questions were carefully formulated. Subsequently, a comprehensive research protocol was developed, outlining specific resources such as selected databases for the search, identification of key publications to be considered, and definition of a set of keywords to be used in the search process. The aim of this protocol was to ensure a systematic and exhaustive retrieval of relevant literature for our study.

The article search for the systematic literature review took place in September 2023 and was divided into four stages, as illustrated in Figure 1.
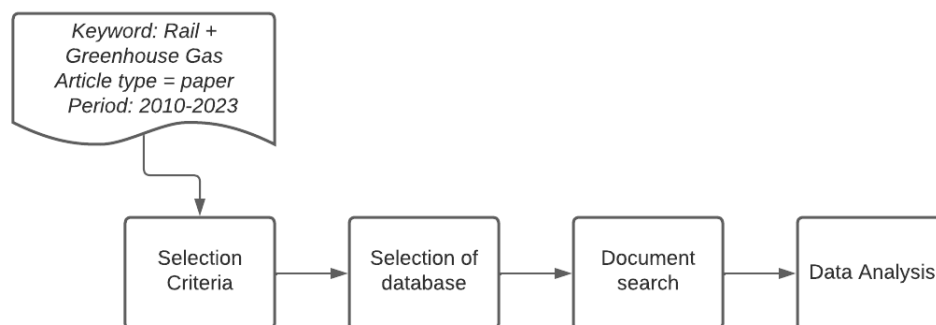
Figure 1. Stages of the articles search for the systematic review.

Selection Criteria: In this stage, the initial criteria for the search were defined, focusing on articles in the research area "Rail and Greenhouse Gas" from 2010 to 2023.

Choice of Database: While there are numerous types of databases for academic documents, Scopus was chosen for this study due to being a scientific database containing a large number of publications, authors, and journals that meet peer-reviewed scientific quality standards [26,29–34]

Document Search: The first search using the terms "Rail + Greenhouse Gas" resulted in 665 documents for the period 2010 to 2023. Subsequently, additional filters were applied, resulting in 327 documents that met the established criteria, as presented in Table 1.

Table 1. Summary of searches performed on the Scopus database.

Searches	Keyword	Filter	Result	Comment
1st	Rail + Greenhouse Gas		665	Not very discriminatory
2nd	Rail + Greenhouse Gas	Year: Between 2010 and 2023	561	A 13-years dataframe was chosen as indicated by most authors for analysis in this field of science
3rd	Rail + Greenhouse Gas	Document type: Articles	351	Articles passes through peer-review, which indicates higher quality
4th	Rail + Greenhouse Gas	Publication stage: Final	327	Documents under publishing processes were not included.

During the implementation phase, suitable research works were identified from the recruited resources based on relevant implementation criteria. Resources that met the implementation criteria were collected, and relevant information pertaining to the research questions was extracted. In the reporting stage, a systematic review article was prepared after investigating the research questions using the collected information.

3. 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 [35].

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 [11,36]. 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 [37]. 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 [38]. 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 [39].

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 [40].

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 [25,41–43].

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 [44,45].

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 [46].

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 [46].

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 [46].

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% [47]

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 [47].

This research underscores the importance of considering not only the electrification technology itself but also the origin of the electricity used to power railway systems. 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 [47].

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 [48].

It's worth noting that carbon emissions are also related to operational practices and proper maintenance of tracks and trains [49–51]. 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 [35,52].

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 [53].

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 [54–57].

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 [58].

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 [59].

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 [59].

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 [59].

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 [59].

The study conducted by Yu [59] 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.

4. Trends in Greenhouse Gas Emission Studies in Railway Systems

The trends in studies concerning greenhouse gas emissions (GHG) in railway systems align with the global need to address climate change. The pursuit of more sustainable and efficient solutions in the railway transport sector continues to evolve, reflecting the growing importance of mitigating emissions and promoting greener and more responsible transportation. Studies are increasingly focused on understanding and reducing GHG emissions in railway systems as part of global efforts to combat climate change. There is a growing awareness of the importance of cleaner and more efficient transportation systems.

There is a rising interest in comparing GHG emissions from railway systems with other modes of transportation, such as highways and aviation. This helps identify the advantages and disadvantages of each mode and informs sustainable transportation policies [9,39]. The electrification of railways, along with the use of renewable energy sources, is gaining prominence. Studies are exploring how electrification can reduce GHG emissions and how the incorporation of clean energy can further enhance environmental efficiency [45]. Research is investigating innovative technologies, such as energy regeneration systems, aerodynamic improvements, and operational optimization, that can contribute to the reduction of GHG emissions in railway systems [55].

Public policies related to climate change and sustainability have influenced studies on GHG emissions in railway systems. Researchers are assessing how policies incentivizing electrification, infrastructure investment, and regulations can impact emissions [11]. Studies are using modeling to project future GHG emissions in railway systems based on different context of growth, electrification, and technology adoption. This helps identify emissions reduction pathways. The analysis of GHG emissions in railway systems is increasingly considering regional and global specificities, including differences in energy matrices, population density, travel patterns, and government policies [60].

5. Calculation Model Used in the Research on Carbon Emissions in Railway Transportation

There are two main approaches to calculate carbon emissions in urban railway transportation. The first is based on energy consumption at the end use and associated carbon emission factors. The second involves direct measurement of CO_2 emission factors, considering travel distance and the mode of transportation used.

In the first method, carbon emissions are calculated by considering the amount of energy consumed by the railway system during its operation. This includes electricity consumption for moving trains, station lighting, air conditioning systems, among others. The consumed energy is then related to carbon emission factors, which indicate the amount of carbon dioxide released into the atmosphere per unit of energy consumed. This approach considers the carbon footprint of the entire system and is often used in life cycle analysis studies [19,61].

In the second method, direct measurement of CO_2 emission factors is carried out based on travel distance and the mode of transportation. This involves collecting data about the trips taken, including the distance traveled and the type of transportation used, such as subway, train, or tram. From this data, CO_2 emissions associated with each mode of transportation are calculated, taking into account the specific operational characteristics of each. This approach is more direct and can provide immediate insights into carbon emissions in terms of distance traveled [62].

Both approaches are valuable for assessing carbon emissions in urban railway transit and are often used in comparative studies between different modes of transportation and

policy analyses for emission reduction. The choice between these methods depends on data availability, study objectives, and the desired accuracy in estimating carbon emissions.

Table 2 summarizes and analyzes some of the research work on rail GHG emissions analysis and measurement in the literature.

Table 2. GHG emissions measurement model of rail in literature.

Country	City	Research Boundary	Summary	Reference
United States	Texas	LCA	Study of greenhouse gas emissions from metro construction, operation, and maintenance	[18]
Brazil	Pernambuco	Operation and maintenance	Study of greenhouse gas emissions from metro operation and maintenance	[61]
Korea	Gwangju	Construction and building	Study of greenhouse gas emissions from railway construction	[63]
China	shanghai	LCA	Study of greenhouse gas emissions from metro construction, operation, and maintenance	[64]
Austria	Vienna	LCA	Ignoring carbon emission from maintenance, dismantling, and recycling phases	[65]
United States	Los Angeles	LCA	Two different LCA frameworks are used	[66]
United States	Phoenix	LCA	Developed an integrated transportation and land use LCA framework	[67]
China	Beijing	Construction and building	A quota-based GHG emissions quantification model for metro station construction is proposed	[68]
Canada	Toronto	Operation and maintenance	Study of GHG emissions from the construction and reconstruction of the Spadina streetcar route	[38]
United Kingdom	London	Operation and maintenance	Analyzed the impact of changes in passenger travel behavior on GHG emissions from metro	[69]
United States	New Jersey	Construction and building	Different material inputs were evaluated during the construction of the railroad project	[70]
Italy	Rome	LCA	The use of data sourced from metro operators reduces the uncertainty of the results	[71]
Turkey	Kayseri	LCA	Integrating environmental, economic, and social factors with the LCA approach	[13]
China	Beijing	Operation and maintenance	No carbon emission by default for power generation methods other than thermal power	[24]
Índia	Delhi	Operation and maintenance	The impact of transport mode shift due to the introduction of the metro on carbon emission is considered	[72]
China	Baoji	Operation and maintenance	Developed a passenger demand-based carbon emission model	[73]

*5.1. Lifecycle-Based Greenhouse Gas Emission Calculation*

Most studies that utilize the approach based on final energy consumption and carbon emission factors focus on measuring carbon emissions during the operational phase of urban railway systems. In this method, the calculation of greenhouse gas (GHG) emissions is conducted by multiplying the electric energy consumption of urban railway systems by the associated carbon emission factor for electricity. This approach takes into account the total electric energy consumption necessary to operate the railway system, including train movement, lighting systems, ventilation, and other components. The energy consumption is then multiplied by the carbon emission factor of electricity, which represents the amount of CO_2 released into the atmosphere per unit of consumed electric energy. This multiplication provides an estimate of the carbon emissions associated with the operation of the railway system.

Life Cycle Assessment (LCA) in the railway system is a comprehensive approach for evaluating the emission of GHGs throughout all phases of the life cycle of a railway system, from raw material extraction to final disposal. LCA considers the environmental aspects related to material production, construction, operation, maintenance, and eventual disposal of a railway system [19]. LCA is a valuable tool for quantifying and evaluating GHG emissions and other environmental impacts associated with the railway system. It enables an objective comparison among different design, operation, and maintenance alternatives, identifying key areas where improvements can be made to reduce environmental impact [20].

The study conducted on the Pernambuco metro aimed primarily to analyze greenhouse gas (GHG) emissions associated with the operation and maintenance of this transportation system. The study found that the total GHG emissions over the life cycle of the Pernambuco railway system, excluding the construction phase, amounted to 6170.54 metric tons of carbon dioxide equivalent (tCO2e). This value represents the overall impact of GHG emissions from the operation and maintenance of the system, as the study did not consider the construction phase due to a lack of data [61].

Based on an estimated system lifespan of 50 years, the study also projected future emissions, estimated to be equivalent to 308,550 tCO2e. This underscores the importance of considering the complete life cycle of a railway system when assessing its environmental impact, as emissions are not limited solely to the operational phase but also include the construction phase and potential maintenance over the years [61].

The railway system in Pernambuco, Brazil, consists of a section of trains powered by diesel traction and another section powered by electricity. As a result, emissions from electricity account for 61% of the total emissions, while emissions from diesel traction represent about 23%. This differs from most railway systems around the world, which are predominantly powered by electricity, Figure 2 [61].
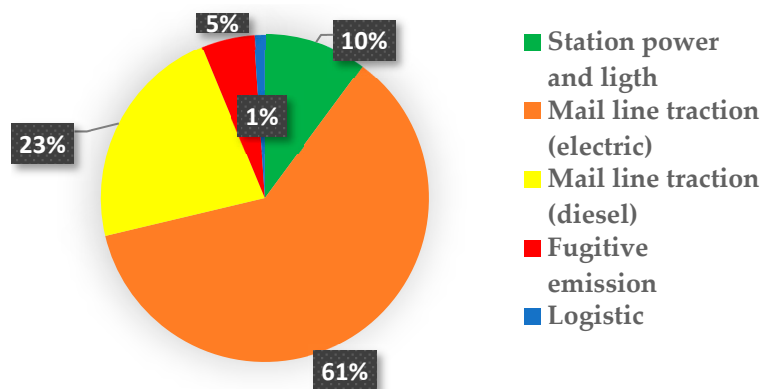
Figure 2. Composition of consumption and emissions of Pernambuco metro; reproduced from [61].

These results are crucial for understanding the role of GHG emissions in the sustainability of the railway system in Pernambuco and for guiding potential mitigation strategies. The study provides valuable information for making informed decisions to reduce emissions over time, whether through improvements in energy efficiency, adoption of cleaner energy sources, or implementation of more sustainable maintenance practices. This research contributes to raising awareness about the environmental impact of railway transportation and provides a starting point for the implementation of measures aimed at making the system more environmentally responsible and contributing to climate change reduction.

A study conducted in China employed the life cycle assessment (LCA) methodology to define the life cycle system of the Shanghai Metro, along with compiling observed real-world data on resource inputs and generated emissions. The study also conducted a comparative analysis of greenhouse gas (GHG) emissions from various urban railway systems worldwide [64].

The results indicate that the total GHG emissions over the life cycle, considering the complete construction extension of the Shanghai Metro with a 50-year lifespan, amount to 109,642.81 metric tons of CO_2 equivalent. Material production, material transportation, on-site construction, operation, and maintenance were responsible for approximately 4.1%, less than 0.1%, 0.4%, 92.1%, and 3.4% of the total emissions, respectively. While GHG emissions per passenger-kilometer traveled of the Shanghai Metro present global competitiveness, the study points out that there is significant energy-saving potential during the operational phase, especially in railway stations with more sustainable designs [64].

The preliminary conclusions of this study provide an understanding of the potential emissions reduction in urban railway transit systems, contributing to emissions reduction goals in China. Furthermore, the results can serve as a valuable source of information and data for future life cycle assessments (LCAs), aiding in the formulation of emissions mitigation strategies in similar transportation systems.

A study in Korea employed LCA to quantify GHG emissions originating from construction modules encompassing various stages such as earthwork, civil engineering activities (including tunnel, viaduct, and bridge construction), railways, passenger stations, and power transmission and telecommunication systems for all HSR lines. Additionally, the study identified the primary activity within each module. The study also analyzed the interdependence between GHG emissions and civil engineering works. This study provided an estimate of GHG emissions during the construction phase of a high-speed railway (HSR) infrastructure connecting Osong to Gwangju, South Korea, inaugurated in 2015. Total GHG emissions reached approximately 3.7 million metric tons of carbon dioxide equivalent (MtCO2eq.), with about 92% of the life cycle GHG emissions was due to vehicle operation and maintenance [63].

The study conducted in Belgium offered a comprehensive assessment of the environmental impact of freight railway transportation in the country, using the life cycle assessment (LCA) methodology. This study analyzed various aspects related to railway transportation, including different types of trains and energy sources used for traction, in order to understand the environmental impact associated with each of these options. The LCA adopted in this study considered not only direct processes related to transportation activities, such as energy consumption and direct emissions, but also other factors involved in the railway system, such as energy production, manufacturing of railway equipment, and the necessary infrastructure for operation. The study divided the freight railway transportation system into three distinct subsystems: operation, railway equipment, and infrastructure [22].

The results indicated that electric trains exhibit superior environmental performance compared to diesel trains in Belgium. The use of electric trains, driven by the Belgian electricity supply mix of 2012, led to a significant reduction in climate change-related environmental impact, reaching a reduction of 26%. Furthermore, the study suggested that increasing the use of electric trains in the future will have a significant impact on the environmental and energy aspects of freight railway transportation. The growing adoption of sustainable electric energy for the operation of electric trains can lead to a more efficient and environmentally friendly freight railway system [22].

The study conducted in the Houston-Dallas corridor (I-45) employed a life cycle assessment (LCA) approach to predict and evaluate net changes in environmental impact associated with the potential development of a high-speed railway (HSR) system along this corridor. The primary objective was to estimate the environmental impact, particularly in terms of carbon dioxide (CO_2) emissions and GHG emissions per vehicle/passenger-kilometer traveled (V/PKT) over the entire life cycle of the system. The study adopted a comprehensive approach, considering various phases of the railway system's life cycle, including material extraction and processing, infrastructure construction, vehicle manufacturing, system operation, and end-of-life. The Ecoinvent 3.4 inventory database was used as a data source for the analysis [18].

The study's results highlighted some important conclusions. Vehicle operation and maintenance were identified as the primary contributor to the total potential global warming, accounting for about 93% of the life cycle. Regarding the infrastructure component, the phase of material extraction and processing was identified as the major contributor, representing approximately 56.76% of GHG emissions, with around 23.75 kg CO_2 eq./VKT. In comparison, the study revealed that various emissions associated with the high-speed railway system throughout its life cycle, except for particulate matter (PM), are significantly lower than those emitted by passenger cars [18]

Another important study conducted a comprehensive assessment of the life cycle sustainability of a light rail transportation system in Kayseri, Turkey. The assessment incorporated environmental, economic, and social aspects to provide a holistic understanding of the system's sustainable performance. For the environmental assessment, a Life Cycle Assessment (LCA) approach was employed using SimaPro 8.4.1 software, in accordance with ISO 14040 and 14044 standards. Nine categories of environmental impact were considered to assess the environmental performance of the light rail transportation system, with a functional unit of 1 passenger-kilometer. The results indicated that the global warming potential and abiotic depletion potential of the light rail transportation system per passenger-kilometer were 2.4×10^{-2} kg CO_2 eq. and 2.7×10^{-1} MJ, respectively, considering a 50-year lifespan [13]

Economic assessment was conducted through life cycle costing, using the functional unit of 1 US dollar per 1 passenger-kilometer. The total life cycle cost of the light rail transportation system was calculated as 0.046 USD per 1 passenger-kilometer. The results highlighted that energy cost was the primary contributor to the total life cycle cost, accounting for about 92% of the total cost. Regarding the social performance assessment, the study identified that the light rail transportation industry demonstrates good performance in terms of benefits for society, the local community, and workers. However, social performance in relation to consumers was evaluated as weaker due to a less effective feedback mechanism [13]

In summary, life cycle assessment (LCA) studies of greenhouse gas emissions in railway systems are essential for promoting the transition to more sustainable transportation systems, enabling the adoption of informed strategies to reduce environmental impacts, optimize efficiency, and promote environmentally friendly practices.

5.2. Calculation of Carbon Emission Factors Based on Distance Traveled and Mode of Transportation

The calculation of carbon emission factors based on distance traveled and mode of transportation is a fundamental approach to estimating GHG emissions associated with transportation activities. This methodology involves determining the amount of CO_2 equivalent emitted per unit of distance traveled in different modes of transportation, enabling a direct assessment of the environmental impact of these activities [74].

First and foremost, the distance traveled is a key parameter in this calculation, representing the length of the journey undertaken. This distance can vary from short urban trips to longer routes between cities or regions. Next, the mode of transportation used is also a crucial factor, as different transportation modes have different energy efficiencies and consequently different GHG emissions. Modes such as gasoline, diesel, electric vehicles, or rail and road public transport have different emission pattern [63].

Carbon emission factors are expressed in terms of the mass of CO_2 equivalent emitted per unit of distance, such as kilometers traveled. These factors can be obtained through measurement data, fuel consumption analyses, direct emissions, or life cycle modeling, depending on the desired accuracy [75].

The combination of these elements—distance traveled and mode of transportation—results in a quantitative estimate of GHG emissions related to transportation activities. These calculations are vital for understanding the environmental impact of different mobility options, aiding in the formulation of sustainable policies, smart urban planning, and

individual transportation choices that contribute to carbon emissions reduction and climate change mitigation [9,76].

In a study in Baoji, the assessment of the environmental impact of urban rail transportation was addressed, focusing on carbon emissions reduction. The study uses the prediction of passenger demand in the city of Baoji in China as a basis to analyze the environmental benefits of the rail transportation system. Scenarios of travel are outlined considering the use of rail transportation and its absence, taking into account the extent of demand generated by different modes of transportation. Carbon emissions from trips are calculated by multiplying the per capita emission of each mode of transportation by the total number of passengers on the target routes. The study highlights the importance of low-carbon urban rail transportation as a sustainable alternative to reduce carbon emissions related to urban transport [73].

A study on low-carbon in Beijing discussed the creation and use of software designed to calculate energy consumption and greenhouse gas emissions in the context of transportation. This software is developed based on research and principles of low-carbon transportation in Beijing, with the main objective of providing a comprehensive tool to assess the environmental impact of various modes of transportation [77].

The process of software development is outlined, including the incorporation of data related to vehicle fleets, energy sources, distances traveled, and other relevant factors. The authors emphasize the flexibility of the software, allowing customization based on specific urban contexts, transportation systems, and policy objectives. It also considers real-time data, increasing its applicability to assess dynamic transportation scenarios. The application of the software is demonstrated through case studies and simulations, focusing on various modes of transportation in the metropolitan area of Beijing. These studies illustrate how the tool can assess the impact of different transportation policies and interventions, providing insights into emission reduction and energy efficiency improvements. This can guide urban planners, policymakers, and researchers in identifying strategies to promote sustainable and low-carbon transportation systems [77].

Furthermore, the article discusses the potential of the developed software to contribute to broader urban sustainability goals, such as reducing traffic congestion, improving air quality, and enhancing overall quality of life. It underscores the importance of integrating energy consumption and emissions analysis into urban planning and transportation management [77].

These studies are important for understanding the environmental impact of the operational phase of urban rail systems and for assessing GHG emissions over time. However, it is crucial to consider that this approach may not capture all emissions associated with the complete life cycle of the system, such as the manufacturing, construction, and maintenance of rail infrastructures. Therefore, a comprehensive analysis of carbon emissions may require the combination of different approaches and the consideration of all stages of the life cycle.

6. The Measurement of Carbon Emissions in Transportation Faces Complexities and Limitations

The life cycle assessment (LCA) is an essential approach to understanding the environmental impact of systems and products throughout all stages of their life cycle, from raw material extraction to disposal. However, the full application of LCA to the railway system may face significant challenges due to the lack of complete and detailed data, especially in the construction stage of railways [78].

The lack of comprehensive data on the construction of older railways can create a gap in the life cycle analysis, particularly when it comes to calculating greenhouse gas emissions (GHG) associated with the construction phase. Many studies that aim to assess the environmental impact of railways might focus on operational and maintenance phases where data is more accessible. The absence of detailed construction data can hinder the accurate estimation of GHG emissions in the construction stage, which, in turn, can lead to an incomplete understanding of the overall impact of railways on climate change. This

can be an obstacle to obtaining a holistic view of the life cycle and conducting accurate comparisons between different modes of transportation or sustainability interventions [79].

To address this limitation, researchers can adopt strategies such as using indirect data, modeling, and simulation to estimate GHG emissions in the construction phase. Furthermore, it's important to acknowledge that LCA is not limited solely to the construction phase; operational and maintenance phases also play a crucial role in evaluating the environmental impact of railway systems. Although the lack of comprehensive construction data may present a challenge, it's essential to consider that LCA can still provide valuable insights into the sustainability of railways throughout their lifespan. Focusing on stages where data is available, along with creative approaches to fill information gaps, can enable researchers to gain a more complete understanding of the environmental impact of railways, even when construction data is limited [22].

In the research conducted on the railway system in Pernambuco, the assessment of greenhouse gas emissions (GHG) exclusively focused on the maintenance and operational phases. This is due to the fact that, due to the age of the railway, construction-related data was no longer available. As a result, the life cycle of GHG emissions ends up being incomplete in this aspect [61]. Previous studies, such as those addressing gas emissions in the Shanghai metro, indicate that the portion of GHG emissions associated with the construction phase is not as significant compared to operational and maintenance phases. In many cases, this portion accounts for only about 5% of the entire GHG emissions cycle of the system. Therefore, while the life cycle assessment (LCA) approach may not be fully comprehensive due to the lack of construction data, this limitation does not seem to have a substantial impact on the final results [64].

This suggests that while the lack of construction data may create a limitation in the comprehensive life cycle analysis of GHG emissions, the focus on operational and maintenance phases, which generally have a larger contribution to the total emissions, still offers valuable insights into the sustainability of the railway system. Therefore, even though the lack of comprehensive construction data may influence the LCA approach, its impact on the final results is relatively limited, especially when considering the proportion of emissions from different life cycle phases.

The quality and comprehensiveness of data used in calculating greenhouse gas emissions (GHG) in the railway system play a fundamental role in the reliability of results obtained by assessment models. The accuracy of estimates depends directly on the availability of reliable and detailed data sources related to the railway transport sector (Manzo et al., 2018). Collecting reliable data is essential to ensure that the calculation model accurately reflects the real conditions of the railway system. Detailed, up-to-date, and comprehensive statistics are necessary to provide a complete view of railway operations, including factors such as distance traveled, type of locomotive used, energy consumption, and operational characteristics. Otherwise, estimates can be inaccurate and either underestimate or overestimate actual emissions [22,78,80].

Furthermore, it is crucial for data sources to be transparent and verifiable. The lack of transparency or unavailability of data used in the calculation can raise questions about the credibility of the results obtained. Obtaining data directly from responsible railway authorities or trustworthy research institutions can enhance the reliability of estimates. Another challenge is ensuring the consistency and updating of data over time. The railway transport sector is subject to changes, such as the introduction of more efficient technologies or the expansion of networks. Therefore, calculation models should be periodically reviewed and adjusted based on updated data to maintain the accuracy of estimates [63].

In a study conducted in China, which presents a comprehensive analysis of the transportation system and evaluates the effectiveness of current strategies aimed at sustainable transportation development, the authors use modeling techniques to assess various transportation scenarios. These scenarios consider factors such as modal choice, infrastructure development, and policy interventions. By simulating different strategies, they analyze

their potential impacts on energy consumption, emission reduction, and overall transportation efficiency.

In the study conducted in China, significant findings related to oil consumption in the Chinese national transportation system were identified. They observed that oil consumption in the national transportation system accounted for 57% of the country's total oil consumption, a much higher proportion compared to the official statistics of 38%. This phenomenon was mainly attributed to the discrepancy between the Chinese energy statistics system and international standards. A relevant explanation for this discrepancy is related to the differences in data collection and calculation methods adopted by the Chinese energy statistics system compared to international standards. The variation in energy accounting systems can result in substantial differences in reported numbers of oil consumption in the transportation sector, which, in turn, affects the accurate understanding of this sector's contribution to total energy consumption and greenhouse gas emissions [81].

In the computational models used to estimate carbon emissions, many of these computational models have limitations in terms of dynamism and adaptability, as many components related to carbon emissions are defined statically. This characteristic can result in inaccuracies in emission calculations over time and in different contexts. Computational models used to estimate emissions should be developed with more dynamism and flexibility, allowing fluctuations in the transportation system over time to be captured more accurately in order to better reflect the operational reality of the transportation system [82].

7. Trends in Research for Greenhouse Gas Emissions Mitigation in the Railway System

As trends in greenhouse gas (GHG) emissions mitigation research within the railway system are evolving towards increasingly comprehensive and innovative approaches as awareness of climate change and the importance of reducing GHG emissions grows, researchers are exploring a variety of areas and strategies to enhance the sustainability of the railway system. This movement reflects the growing need to find innovative and comprehensive solutions to address environmental challenges, underscoring a commitment to building a more environmentally responsible railway system.

A significant trend is the transition to electrified railway systems or other systems with more sustainable fuels, reducing dependence on fossil fuels. This involves adopting renewable energy sources, such as electricity from wind, solar, hydro, or fuels such as hydrogen and biodiesel to power trains. Shifting to a more sustainable fuel helps reduce GHG emissions by eliminating direct emissions from trains and optimizing energy efficiency [83].

A study in the railway system of northeastern Brazil addressed the application of solar photovoltaic systems on light rail vehicles (LRVs). The study explored the feasibility and benefits of incorporating solar technology to assist in the electric power supply of LRVs. The research considers the scenario of sustainable public transportation and the potential advantages of solar energy generation to reduce dependence on conventional sources and mitigate GHG emissions [84].

Another energy efficiency study presented a strategy to optimize water and energy use in public buildings, using a Brazilian railway company as a case study. The study addresses the importance of resource efficiency in public facilities, considering both cost reduction and environmental benefits. The research details the approach taken, including the implementation of measures such as rainwater harvesting, the installation of water-saving devices, and the use of renewable energy systems. The specific case study in the Brazilian railway company demonstrates the results obtained from the implementation of these measures, both in terms of financial savings and the reduction of natural resource consumption and GHG emissions [85].

Studies on the use of hydrogen in trains have gained prominence due to the search for cleaner and more sustainable transportation solutions. Hydrogen is considered a promising energy source for trains, as its combustion or conversion into electricity through fuel cells produces only water as a byproduct, eliminating pollutant emissions and GHGs. Overall, studies on hydrogen use in trains aim to provide comprehensive information on the

technical, environmental, and economic feasibility of this energy alternative, contributing to informed decision-making by transport authorities and promoting the transition to more sustainable railway systems [83].

A study on urban light hydrogen-powered rails explores the modeling, analysis, and practical implementation of an urban light rail powered by hydrogen fuel cells. The study focuses on exploring the feasibility and potential benefits of using hydrogen as an alternative energy source for urban rail transport. The study discusses various scenarios, considering different methods and hydrogen production technologies. This includes assessing emissions throughout the lifecycle and energy consumption of the entire system, from hydrogen production to train operation. The authors also consider the economic viability of implementing such a system, taking into account factors such as initial investment costs, operational expenses, and potential benefits in terms of reduced emissions and energy efficiency [86].

In conclusion, this article presents a comprehensive analysis of implementing a light urban hydrogen-powered rail system. By addressing technical, economic, and environmental aspects, it provides valuable insights into the feasibility and potential benefits of adopting this system. The study's modeling, analysis, and practical considerations contribute to advancing sustainable transportation solutions and encourage further research and development in the field of hydrogen fuel cell technology for urban rail systems [86].

Practical implementation is a crucial aspect as it aims to bridge the gap between theoretical analysis and real-world application. Exploring the technical challenges associated with integrating hydrogen fuel cells into existing rail systems, ensuring safety, reliability, and efficiency. Discussing potential barriers and regulatory considerations that need to be addressed for successful implementation is important for the evolution of sustainable railway transportation. The potential benefits of hydrogen rail systems, including reduced greenhouse gas emissions, improved air quality, and reduced dependence on fossil fuels, are also discussed [86,87].

Another significant research involving hydrogen in the railway system addresses the use of dual-fuel diesel engines operating with diesel injection and the introduction of fumigants such as hydrogen, gasoline, and ethanol. The main objective is to investigate how different diesel injection timing affects efficiency and emissions during multi-fuel combustion. The results show how varying the timing of diesel injection influences combustion efficiency, heat release rate, and emissions. These findings can offer valuable insights for optimizing the operation of dual-fuel engines, contributing to the reduction of pollutant emissions and the search for cleaner and more efficient alternatives in the transportation sector [88].

The use of biodiesel in the railway system is an approach aimed at partially or fully replacing conventional petroleum-derived diesel with a renewable and more sustainable fuel. Biodiesel is a biofuel produced from renewable sources such as vegetable oils, animal fats, or food waste through transesterification processes. Adopting biodiesel in the railway system aims to reduce pollutant emissions and contribute to climate change mitigation, as biodiesel tends to generate fewer carbon dioxide (CO_2) emissions and other atmospheric pollutants compared to fossil diesel. Additionally, biodiesel is biodegradable and produces less particulate matter, contributing to improving air quality in urban areas [20,89,90].

However, implementing biodiesel in the railway system also faces technical and logistical challenges. Ensuring that train engines are compatible with biodiesel blends is necessary, as biodiesel has different combustion properties compared to conventional diesel. Additionally, the availability and quality of biodiesel can vary, which can affect the efficiency of the railway system [91].

Ongoing studies and research are assessing the impacts of biodiesel use in the railway system, such as evaluating nitrogen oxide (NOx) and nitrogen dioxide (NO_2) emissions during the cold start of a diesel engine when fueled with different proportions of diesel and biodiesel blends. The main aim of the study is to investigate how biodiesel blends affect NO_2 and NO_x emissions during the cold start phase of a diesel engine. Cold start is a

critical period in terms of emissions, as engine temperatures are low and combustion is not ideal, which can lead to increased pollutant emissions. The results indicate how different biodiesel blend ratios affect NO_2 and NO_x emissions, highlighting impacts during cold start. This can provide valuable insights for the automotive industry and environmental policy formulation, aiming to reduce pollutant emissions and develop cleaner and more efficient fuels [92].

Another biodiesel research investigates the spray behavior of a common rail diesel injector using a blend of biodiesel with 5% gasoline. The analysis provides information about the spray pattern and how different operational factors impact this process, contributing to a comprehensive understanding of the use of biofuel blends in diesel engines. The results offer insights into the angle, shape, and dispersion of spray droplets, considering different operating conditions such as injection pressure and flow velocity [93].

Researchers are also focusing on improving the energy efficiency of railway systems, such as designing lighter and more aerodynamic trains, energy regeneration systems during braking, and route optimization to reduce energy consumption [30,94,95].

A study addresses computational simulation of the contact response between wheels and tracks in a straight rail scenario. The research focuses on analyzing the behavior of wheel-track contact, taking into consideration different variables such as material characteristics, component geometry, and applied forces. The study utilizes dynamic simulations to understand how forces, deformations, and pressure distribution occur during the contact between wheels and tracks. The simulation results provide valuable information about the distribution of forces and stresses at the contact point, allowing for a deeper understanding of the system's performance and dynamic behavior. This has significant implications for the design and maintenance of railway systems, contributing to operational optimization and the reduction of greenhouse gas emissions [96].

In railway systems, real-time traffic management allows for monitoring and controlling train movement in real-time, identifying potential congestion, delays, or operational issues. This immediate responsiveness enables corrective measures to be adopted, such as adjusting train speed, optimizing stop schedules, and coordinating traffic flow, thus minimizing delays and improving service regularity. The integration of intelligent operation systems into railway systems offers a range of notable advantages. These systems can optimize energy efficiency by determining the best way to use available energy and intelligently managing power distribution. This is particularly valuable in electrified railway systems, where electrification is common, contributing to reduced energy consumption and pollutant emissions [30,97].

Effective integration among different modes of transportation (rail, road, cycling, etc.) allows for a more holistic approach to transportation system planning, reducing overall emissions by promoting more sustainable options.

A study involving an inference model for passenger itineraries in congested urban rail networks employs data from ticketing and train schedule information to estimate the routes and itineraries followed by passengers in congested urban rail transportation systems. Through the analysis of ticketing data and train schedules, the proposed model allows for estimating the most frequently used passenger routes, identifying major traffic flows and congestion points. This information can be used to develop congestion mitigation strategies, such as train redistribution, schedule adjustments, or the implementation of measures to avoid bottlenecks at key stations. This contributes to improving passenger experience and optimizing operations during high-demand situations, aiding in greenhouse gas emissions reduction [60].

In summary, research trends in greenhouse gas emissions mitigation within the railway system reflect a comprehensive approach involving electrification, energy efficiency, multimodal integration, sustainable technologies, and environmentally friendly policies. These trends aim to make railway transportation a more sustainable option and contribute to reducing greenhouse gas emissions in the transportation sector as a whole.

8. Conclusions

The approach of this research focuses on advancements in studies related to carbon emissions measurement in the railway transportation sector, providing a comprehensive analysis of existing research. Currently, there is maturity in analyses that seek to assess the potential reduction of carbon emissions in railway transportation, as well as in defining research scopes, utilizing measurement methods, and developing models. However, this maturity coexists with challenges posed by the inherent complexity of the railway environment, including electricity generation, urban rail expansion, system longevity, and interactions with other transportation modes in a multimodal context.

Within this complex scenario, ensuring the accuracy of carbon emissions measurements emerges as a critical aspect. Appropriate determination of carbon emission factors, judicious selection of measurement steps, and verification of the accuracy and validity of employed data are crucial aspects that need to be considered in future research. The application of life cycle assessment (LCA) methodology in the context of railway emissions is explored, and several articles are used as examples to illustrate this process. Despite the progress made, unresolved issues still remain. For instance, even though the use of LCA has become more systematic and refined, many studies fail to encompass the entire railway life cycle, especially in the initial construction phase.

Measuring carbon emissions in urban railway transportation systems presents multiple challenges and considerations. The precision and comprehensiveness of the required data for these measurements often encounter obstacles, and the very definition of carbon emissions can be ambiguous, complicating the task of accurately and simultaneously measuring emissions from this urban transport.

In summary, despite notable advancements, this research underscores that the intrinsic complexity of the railway transport context and the need for accurate measurements remain significant challenges in carbon emissions investigations within this sector. The application of LCA methodology offers a valuable framework, but the absence of data in certain life cycle phases and the ambiguity in emission definitions represent challenges to overcome in achieving a thorough and accurate understanding of the environmental impact of railway transportation.

To guide future research, it is crucial to direct efforts towards several key areas to enhance the understanding and approach to carbon emissions within the urban railway transportation system:

1. Data Collection and Quality Enhancement: An essential focus should be to ensure the accuracy and comprehensiveness of data detection and collection necessary for analyzing carbon emissions in urban railway transportation systems. This requires improved data acquisition methods and a more rigorous approach to data verification and validation, to enhance the overall quality of estimations.
2. Implementation of Monitoring Systems: Establishing a digital system that tracks greenhouse gas (GHG) emissions throughout the entire life cycle of the railway transportation system is fundamental. This digital twin system can integrate data from various life cycle phases, offering a holistic model and facilitating visualization and monitoring of railway transportation GHG emission measurements.
3. Integration of Multimodal Transport Modes: Most current studies focus on isolated analysis of urban railway traffic, often separating it from multimodal transportation systems. Thus, it is crucial for research to advance towards a more comprehensive analysis, considering the integration of railway transportation with other transportation modes in integrated urban systems, which can more realistically reflect the dynamics of carbon emissions.

Directing research efforts according to the outlined points will lead to significant advancements in the understanding and measurement of carbon emissions in the urban railway transportation system. This will provide essential information for well-founded and effective public policy formulation, contributing to emission reduction, climate change

mitigation, and the promotion of more sustainable transportation. This approach will also have a significant impact on improving the quality of life for future generations.

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