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Estimating Carbon Emissions of Northeast Brazil Railway System

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Abstract: This article addresses the developing of a framework to obtain specific GHG emissions for the railway system and proposes mitigation strategies. To achieve this purpose, a comprehensive life cycle assessment (LCA) method was employed with input data from various sources to analyze the contribution of energy consumption and the emissions of the railway system. This paper included gathering data from an infrastructure operation and maintenance for detailed GHG emissions impact. This study also presents a comparative analysis of the GHG emissions in different urban railway transportation systems in Northeast Brazil, providing valuable contextual insights. As a result of the combination of total GHG emissions analysis from the states of the Northeast Brazil railway system, a total of 11,996.11 metric tons of CO_2 equivalent (tCO_2e) was estimated. The main line traction was a prominent source of the greenhouse gas footprint, especially for the diesel traction systems at Paraiba. The proposed framework shows that significant environmental benefits can be realized with proper decision-making to increase the number of passengers–kilometer transported by rail.

Keywords: railway; GHG emission; electrification; climate change; policies

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1. Introduction

In recent decades, the rapid growth of the population and urbanization has led to an increasing demand for alternative transportation services in societies. This emerging trend in mobility requires swift responses from public transportation systems, which must offer reliable, comfortable, and economically and environmentally sustainable services. As economies thrive and cities expand, an efficient transportation infrastructure can play a vital role in mitigating environmental issues, diseases, and fatalities in urban areas [1,2].

The issue of greenhouse gas (GHG) emissions has become one of the most pressing and crucial concerns on a global scale, driven by the growing understanding of its implications for climate change. As an essential element of the worldwide initiatives aimed at addressing climate transformations, multiple sectors have been examined regarding their contribution to GHG emissions. In this context, the railway transportation system has emerged as a fundamental area of investigation, given its significance in urban mobility and freight transport [1,3].

The railway system, although often seen as a more sustainable transportation option compared to road and air modes, is not exempt from significant environmental impacts. The combustion of fossil fuels, such as diesel, to power trains is one of the primary sources of GHG emissions in the railway sector. This generates carbon dioxide (CO_2) and other gasses that contribute to global warming [4].

A comprehensive literature review on greenhouse gas emissions in the railway system unveils a complex interplay of factors contributing to the generation of these gasses. Studies have indicated that the electrification of the railway system, replacing diesel traction with electricity, can substantially decrease GHG emissions. The adoption of cleaner and renewable energy sources for the electricity used in trains can be a crucial step in mitigating emissions [5–15].

Additionally, the effectiveness of operations and the adoption of traffic management technologies can influence GHG emissions. More modern and energy-efficient train models tend to release lower amounts of GHGs per kilometer traveled, in contrast to older and less efficient models. Appropriate maintenance measures and route optimization also prove to be contributing factors in reducing emissions [16–19].

Another relevant aspect is waste management and fugitive emissions, which can occur during the transportation and maintenance processes of railway systems. The proper maintenance of railway tracks and the appropriate management of train components can minimize these emissions [16,17].

The utilization of life cycle assessment (LCA) methods has proven to be a highly useful tool for examining the effect of GHG emissions throughout the entire life cycle of the railway system. These methods enable the analysis of emissions from material production to train operation and maintenance, providing a comprehensive understanding of the emissions involved [18,20–24].

The environmental impact of greenhouse gasses in the railway context highlights the intricate interplay of the factors influencing emissions, underscoring the significance of comprehensive approaches to mitigation. Electrification and enhanced operational efficiency emerge as fundamental elements to attenuate the environmental impact of the GHG emissions from the railway system, thereby contributing to the promotion of sustainability and the fight against climate change [21,25].

While there are studies that delve into environmental performance through life cycle assessment (LCA), there is a shortage of literature specifically examining life cycle assessments in railway systems, particularly concerning greenhouse gas emissions [26]. Consequently, there is an urgent need to research greenhouse gas emissions and environmental impacts in the railway system and identify effective mitigation strategies for these emissions.

The impact of greenhouse gas emissions in the railway system stands as an indispensable tool to underpin effective public mitigation policies. By providing meticulous and precise data on emissions, this work allows for a focused approach to reducing emissions throughout the entire life cycle of the railway system. Such a focus directly contributes to the promotion of environmental sustainability, addressing climate transformations, and building a more resilient and adaptable future [27–30].

Therefore, the objective of this study was providing an analysis of the greenhouse gasses in railway system emissions using a life cycle methodology approach. This analysis employed a life cycle assessment methodology to accurately map the carbon footprints associated with these emissions. As a result, this work calculated the greenhouse gas emissions generated by the metro system in Northeast Brazil, which comprises the states of Paraiba, Pernambuco, Rio Grande do Norte, and Alagoas. This study aimed to compare these emission results with the studies in global railway greenhouse gas emissions. Additionally, it sought to analyze ways to mitigate these greenhouse gas emissions to formulate more effective public and environmental policies within the railway transportation system of these regions.

2. Materials and Methods

2.1. Study Area

This research was conducted on the railway system in Northeast Brazil, specifically focusing on the states of Paraiba, Pernambuco, Rio Grande do Norte, and Alagoas, which are equipped with this transportation infrastructure.

The railway is distributed in different municipalities in the states of Northeast Brazil, as shown in Figure 1: Paraiba (João Pessoa, Cabedelo, Santa Rita, Bayeux); Alagoas (Rio Largo, Setuba, Maceio); Rio Grande do Norte (Ceará-Mirim, Extremoz, Natal, Parnamirim); Pernambuco (Recife, Jaboatão dos Guararapes).

The rail system encompasses an electric metro that operates through an overhead power grid for electrification, along with a diesel train. Spanning over 200 km in length, this extensive transportation network caters to an average daily ridership of 250,000 passengers.

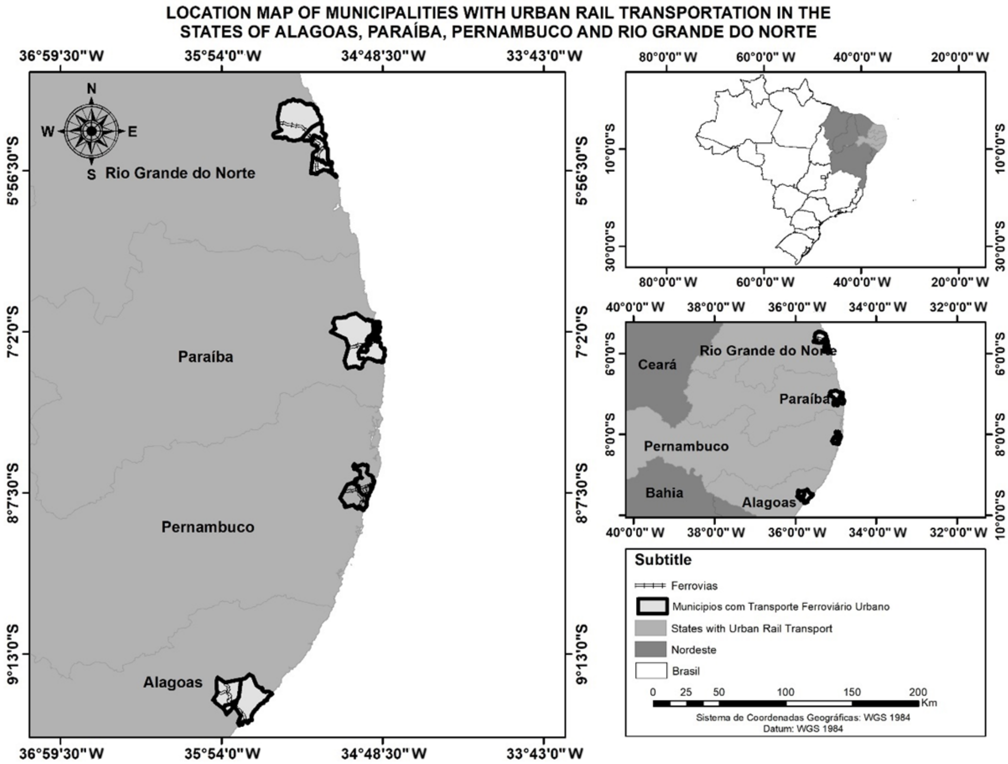

Figure 1. Location map of the northeastern railway system, Brazil.

2.2. Methods

The method employed in this investigation was using the quantitative emissions across the life cycle, with the calculations taking into account the associated resource inputs (materials, fuels, and equipment).

A life cycle assessment (LCA) is an international methodology used to quantify the emissions of specified products or systems throughout their entire lifecycle [31]. However, this methodology was originally defined to be applied to various types of products in a generalized manner. Therefore, conducting an LCA for a railway system can be much more complex than for consumer products in general. Since the urban railway transportation system is not merely a product, commodity, or project, none of the standards can fully apply to it [32]. Modeling may not be sufficient and may require adaptations. Selections concerning system boundary definition, model parameterization, and data selection can significantly impact the calculated results.

For the environmental assessment, a life cycle assessment (LCA) approach was employed using SimaPro 8.4.1 software following the parameters of ISO 14040 and 14044 [32–34]. According to LCA publications choices regarding system boundary definition, model parameterization, and data selection can significantly affect the calculated results [35–38].

In this study, the parameters of the GHG Protocol Product Standard from the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) were used. The methodology used was quantitative and based on the specifications of the Brazilian GHG Protocol Program published by the World Resources Institute [39] for corporate greenhouse gas emissions accounting, quantification, and reporting.

The urban railway transportation system comprises tracks, tunnels, viaducts, power facilities, depots, stations, vehicles, and control centers [38,40]. The calculation encompassed the associated resource inputs (materials, fuels, and equipment) and greenhouse gas emissions outputs at each phase, as shown in Figure 2.

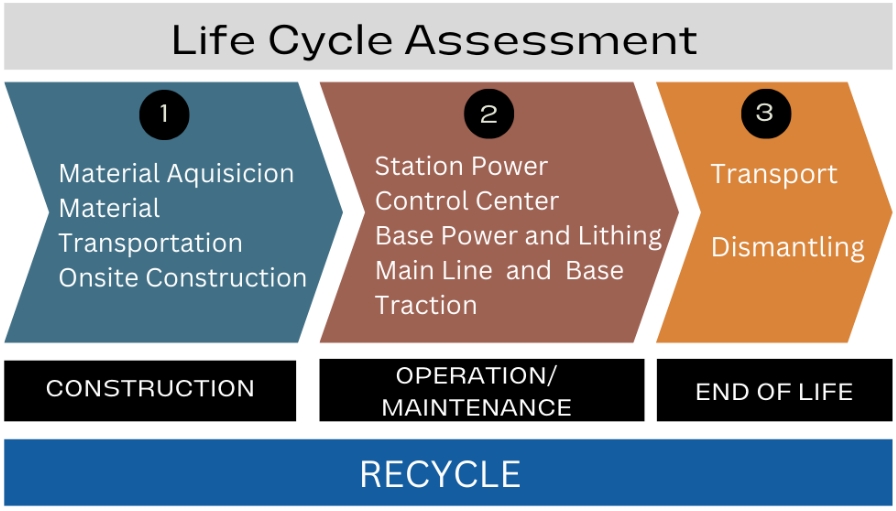

Figure 2. Flowchart of greenhouse gas emissions methodology for LCA railway.

There is an adapted version for the Brazilian product system, but it has not been thoughtfully tailored to the railway system, lacking the diesel railway system currently used in Northeast Brazil in its modeling parameters. This investigation will model this calculation parameter based on the existing indices from the World Resources Institute.

Due to Brazil's northeastern railway system having existed for over 150 years, there are no data available regarding its construction, such as project budget spreadsheets with detailed and complete records of the construction process. As a result, this research will not cover the emissions from the railway's construction phase.

This work displays the total amount of gas emissions based on the year 2022; however, to compare with other international case studies, the results were standardized per passenger–kilometer traveled (PKT) [29].

2.3. Life Cycle Assessment Modeling

Each greenhouse gas has the ability to absorb infrared thermal radiation over 100 years, and this capacity can be compared to the ability of carbon dioxide to perform the same function over the same period of time. For calculating CO_2e, we used the Global Warming Potential (GWP) to compare the global warming impacts based on the emissions estimates of different gasses [41–44], as shown in Table 1.

Table 1. Category of factors for greenhouse gas emissions.

GAS	GWP-100
CO_2	1
CH_4	25
N_2O	298
HFC-125	3500
HFC-134a	1300
HFC-143a	1430
HFC-152a	124
CF_4	7390
C_2F_6	12,200
SF_6	22,880

Source: Adapted [45].

Most of the studies we found were focused into four phases: the production, construction, operation, and maintenance of railway infrastructure [46–49]. They approached the production stage considering all the raw materials and structural components to manufact train car bodyshells and infrastructure projects, where the scarcity of papers about LCA applied on railway vehicles use was shown. This modeling involved calculating the inputs of the associated resources (materials, fuels, and equipment) and the outputs of the greenhouse gas emissions at each phase, categorized by operation, maintenance, transportation, and material procurement from the construction sectors [50,51].

The life cycle greenhouse gas emissions were estimated using Equation (1), as follows:

$$E = (Q1 + Q2 + Q3 + Q4)/L, \quad (1)$$

where

E = greenhouse gas emissions per unit length of the urban railway transportation system (tCO_2e/km);

Q1 = maintenance emission factor;

Q2 = operation emission factor;

Q3 = transportation emission factor;

Q4 = material procurement emission factor;

L = length of the railway track (km).

Calculation of Operation and Maintenance Emission Source

- Fugitive Emission

The calculation of the carbon dioxide equivalent (CO_2e) emissions from refrigeration, air conditioning, and fire extinguishing equipment can be carried out by following the following general steps: identifying all the refrigeration, air conditioning, and fire extinguishing equipment present in the system; identifying the GHGs by determining the specific greenhouse gasses used in each piece of equipment; obtaining the necessary data to perform the calculations, including information about the quantity of GHGs used, the specific emission factors for each GHG, and the equipment efficiency. This model uses the emissions from hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).

To calculate the GHG emissions from refrigeration and air conditioning equipment and fire extinguishers using a life cycle stage approach, Equation (2) is as follows:

$$E = (EUN + EUE + EUD) * GWP, \quad (2)$$

where

E = emissions in CO_2e (kg);

EUN = emissions from the installation of new units; gas is used to charge the new equipment minus the equipment's capacity (the difference corresponds to losses to the atmosphere);

EUE = gas added to the existing units as maintenance by the organization or supplier (does not include the pre-charging performed by the manufacturer);

EUD = emissions from the disposal of old units; the capacity of the discarded unit minus the amount of recovered gas (the difference corresponds to losses to the atmosphere);

GWP = the Global Warming Potential of the greenhouse gasses (Table 1).

- Rail transportation

The rail fleet in Northeast Brazil is characterized by three types of trains: locomotives, light rail vehicles (VLT), and electric trains. The first two utilize commercial diesel oil as fuel. In Brazil, due to regulation, some fossil fuels are legally required to have a percentage of biofuel incorporated before being sold to the final consumer (ANP Resolution No. 909/2022). Therefore, the calculation is performed separately for pure fossil diesel oil and biofuel B10, with 90.00% fossil fuel diesel oil.

Initially, the values of fossil fuel and biofuel are separated. Then, the emission factors for the use of fossil fuels and biofuel in mobile sources are used for greenhouse gas conversion, as shown in Table 2.

Table 2. Emission factors for fossil fuel diesel oil and biodiesel.

Fuel	Kg CO_2/L	Kg CH_4/L	Kg N_2O/L
Fossil Diesel Oil	2.681	1.385×10^{-4}	1.385×10^{-4}
Biodiesel	2.499	3.316×10^{-4}	1.99×10^{-5}

Source: Adapted [39].

- Emissions in metric tons of CO_2

$$E = ECOF \times GWP\_CO_2 + ECHF\ (t) \times GWP\_CH_4 + ENOF(t) \times GWP, \quad (3)$$

where

E(t) = total emissions (tCO_2e);

ECOF = CO_2 emissions (t) fossil (the sum of the total fossil fuel quantity (L or m^3) $\times$ the fossil fuel emission factor (kg CO_2/L)/1000;

ECHF(t) = CH_4 emissions (t) (the sum of the total commercial fuel quantity (L or m^3) $\times$ the commercial fuel emission factor (kg CH_4/L)/1000;

ENOF(t) = N_2O emissions (t) (the sum of the total commercial fuel quantity (L or m^3) $\times$ the commercial fuel emission factor (kg N_2O/L)/1000.

- Emission of biogenic CO_2

$$EB(t) = FEB \times SQB, \quad (4)$$

where

EB(t) = biogenic CO_2 emissions (tCO_2);

FEB = biofuel emission factor;

SQB = sum of total biofuel quantity present in commercial fossil fuel, mandated by Brazilian law, in L.

In addition to CO_2 emissions, other greenhouse gasses can be emitted during fuel combustion. Therefore, if it is necessary to calculate emissions of other GHGs, the use of GHG emission factors is important.

- Electric Energy

Due to the source of electric energy in Brazil mainly coming from large hydroelectric, thermal power plants, nuclear energy, and renewable energy, there is a monthly variation in the energy sources and they complement each other in case of shortages. The small variation in the monthly CO_2 average emission factors of the national grid presents a relationship with seasonal fluctuations of the variable power generation of renewable sources. Furthermore, these intensities also change every year, and the Ministry of Science and Technology provides the conversion table annually.

For greater accuracy, a calculation of the greenhouse gas emissions from the monthly consumed electric energy was performed. The emission factors for the electricity generation, varying each month supplied from Brazilian Interconnected System (SIN), are shown in Table 3.

- Greenhouse Gas Emission Calculation Equation for Electricity Purchase

$$E(t) = \sum_{n=1}^{\infty}\left(\frac{CEM\_jan \times FEM\_jan}{1000} + \frac{CEM\_feb \times FEM\_feb}{1000} + \cdots + \frac{CEM\_dec \times FEM\_dec}{1000}\right) \quad (5)$$

where

$E(t)$ = mass of CO_2 emissions from electricity (tCO_2);

CEM_m = quantity of electricity that is consumed (MWh) in the month;

FEM_m = emission factor of SIN in the month.

- Calculation of Emission Source for Transportation (Logistics)

The calculation of the carbon dioxide equivalent (CO_2e) emissions from road transportation that utilize greenhouse gasses (GHGs) for the movement of equipment, personnel, and materials for railway operation and maintenance is carried out by identifying the types of transportation and the types of fuels (diesel, gasoline, ethanol, natural gas, etc.) used by road vehicles. Then, the values of the emission factors of each fossil fuel and biofuel are separated and applied for GHG conversion in mobile sources, as per Table 4.

Table 3. Emission factors for electricity generation.

Parameters for the 2019 Inventory	
Month	**FE of SIN (tCO_2/MWh)**
Jan	0.0355
Feb	0.0667
Mar	0.0530
Apr	0.0514
May	0.0482
Jun	0.0426
Jul	0.0906
Aug	0.1070
Sep	0.1024
Oct	0.1040
Nov	0.1078
Dec	0.0919

Source: Adapted [52].

Table 4. Global Warming Potential (GWP) of greenhouse gasses.

Fuel	**Unit**	**Emission Factors (kg CO_2/L)**		
		CO_2	**CH_4**	**N_2O**
Automotive Gasoline (pure)	L	2.212	0.0008	0.00026
Diesel Oil (pure)	L	2.603	0.0001	0.00014
Compressed Natural Gas (CNG)	m^3	1.999	0.0034	0.00011
Liquefied Petroleum Gas (LPG)	kg	2.9325	0.0029	0.00001
Aviation Kerosene	L	2.52	0.00002	0.00007
Aviation Gasoline	L	2.25	0.00002	0.00006
Lubricants	L	2.7175	0.0001	0.00014
Fuel Oil	L	3.1	0.0004	0.00002
Hydrous Ethanol	L	1.457	0.0004	0.00001
Biodiesel (B100)	L	2.431	0.0003	0.00002
Anhydrous Ethanol	L	1.526	0.0002	0.00001

Source: Adapted [44].

The GHG emissions from CO_2, CH_4, and N_2O of the commercial fuel and biofuel were calculated using the conversion factors for CH_4 (kg/L) and for N_2O (kg/L) by type, year, and fleet fuel. In the same way, to estimate the GHG emission, the consumption data per type of fuel we used Equations (3) and (4).

3. Results

3.1. Raw Material Production, Transportation, and On-Site Construction

The structure of urban railway transportation in Northeast Brazil dates back more than 150 years, as the Brazilian government strategically chose to repurpose the inactive freight railway to build the urban railway. Therefore, there is no real information available about the construction of the urban railway in Northeast Brazil. Due to this reason, the inventory of greenhouse gas (GHG) emissions from the construction of the railway is not discussed in this case study.

Based on other studies like the article "Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro" [29] the emissions from the construction of a railway track represent less than 5% of the entire life cycle of a railway system. Therefore, the lack of construction data does not have a significant impact on the model.

3.2. Operation and Maintenance

The energy consumption of the operation and maintenance phases can be divided into eight sources: fugitive emissions, station energy and lighting, electric line traction, diesel line traction, base energy and lighting (workshop and administration), control center energy and lighting, and transportation and materials [21,31,53,54]. To serve as a reference for future life cycle assessment (LCA) studies on urban railway transportation systems, the scope of each source is described below, in Table 5.

Table 5. Energy consumption data.

Source	Energy Consumption	Emissions (tCO_2e)	CO_2-Biogenic
Electric (building)	9455.21	700.60	-
Logistic transportation (diesel)	30,923	11.23	11.23
Logistic transportation (gasoline)	86,472	184.31	45.05
Fugitive emissions	1397.98	1035.45	-
Electric train traction	51,663.668	3774.70	-
LRH (diesel)–train traction	19,78746	5648.34	555.20

Considering data availability and accessibility, the year 2022 was chosen as the base year to estimate the overall emission level of the operation and maintenance phases. According to the data obtained from the Brazilian urban train company, the total energy and resources consumed in logistic transportation, including car and truck entries and exits, account for the lowest among all the related sources as are presented in Table 5. The total energy used in building energy as station power and light are also presented in Table 5, with their associated emissions. We summarized all the air conditioning gasses and fire extinguishers used in the railway system in 2022, as fugitive emissions. The table provides the traction energy consumption for electric and diesel trains, respectively. This traction energy represents around 83% of the greenhouse gas emission (GHG) of the railway system.

Since the railway system in Northeast Brazil relies significantly on diesel-powered trains, the emissions from electric energy do not constitute the majority of emissions, in contrast to most other railway systems globally, which are predominantly powered by electricity, as demonstrated in Figure 3.

Although the emissions do directly originate from the electricity consumption during operation, the life cycle assessment (LCA) calculations incorporated the greenhouse gas (GHG) emissions from the processes of electricity generation and transmission. In the year 2022, the average annual electricity consumed for powering trains in the Northeast Brazilian railway system during the operation phase amounted to 51.7 million kWh. The GHG emissions from the electricity used to power the trains were calculated to be 3774.70 metric tons of CO_2 equivalent (tCO_2e).

In the same year, the diesel-powered train system consumed 1,978,746 L of diesel fuel for its operation. The GHG emissions resulting from this consumption were calculated to be 5703.54 metric tons of CO_2e.

By adding emissions from other energy resources, the total annual GHG emissions from the operation and maintenance activities amounted to 11,996.11 metric tons of CO_2e.

The provided data on greenhouse gas (GHG) emissions in the rail system of Pernambuco, Paraiba, Alagoas, and Rio Grande do Norte, as shown in Figure 4, presents an interesting view of the different emission sources associated with railway operations and related infrastructure.

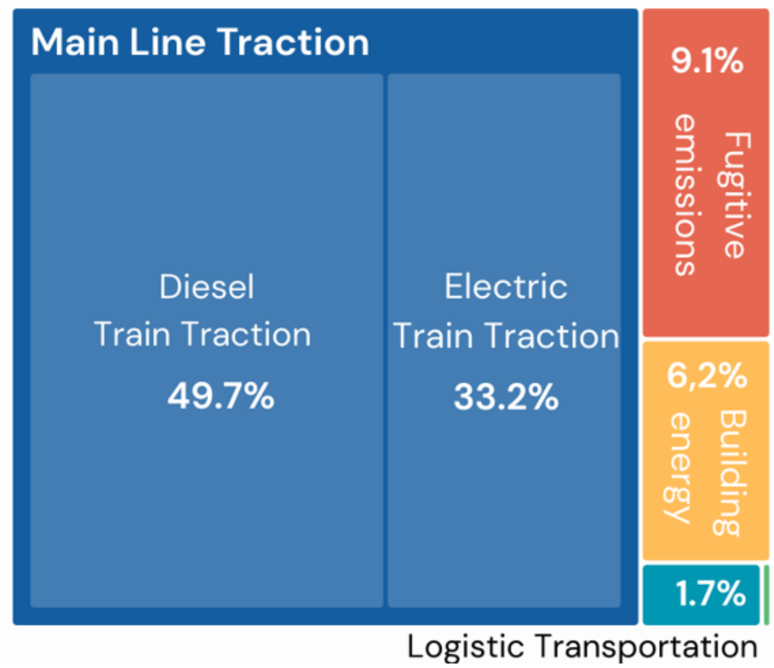

Figure 3. Composition of consumption and emissions in 2021.

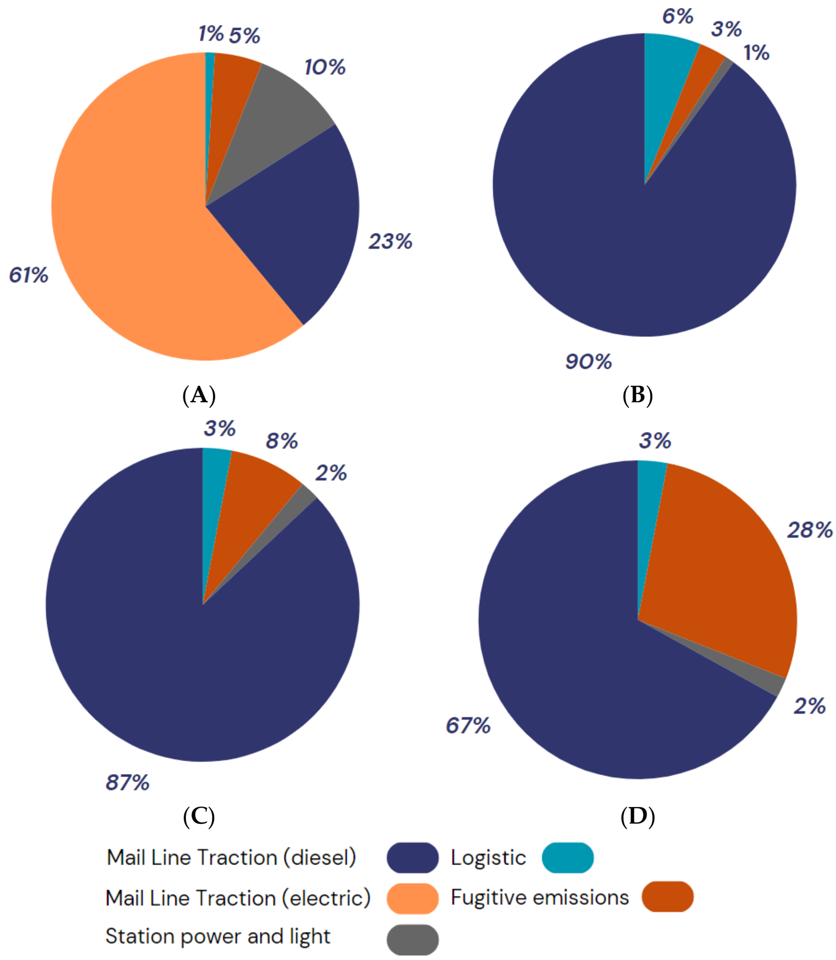

Figure 4. Composition of consumption and GHG emissions of rail system. (**A**) Rail system of Pernambuco. (**B**) Rail system of Paraiba. (**C**) Rail system of Alagoas. (**D**) Rail system of Rio Grande do Norte.

It is evident that GHG emissions vary considerably among the states and between different emission sources. The "Main line traction" category is a prominent source of GHG emissions, both for electric and diesel traction systems. In Pernambuco, for example, electric traction significantly contributes to emissions as the trains are powered by both electric and diesel energy, while in Paraiba, Alagoas, and Rio Grande do Norte, diesel traction is the main source due to the use of diesel-powered light rail vehicles. The emissions from diesel traction can be impacted by factors such as engine efficiency and fleet composition [20,40,55–58].

In summary, these data provide a valuable starting point for assessing the GHG emissions associated with railway operations in different cities. They highlight the need for a comprehensive and context-specific approach to addressing emissions, considering local sources and challenges. By focusing on clean technologies, operational efficiency, and strategic planning, it is possible to significantly reduce the GHG emissions in these railway operations.

The comparison between the states demonstrates the diversity of the energy choices for train traction. While Pernambuco opted for electric traction and thus recorded high emissions associated with electricity consumption, Paraiba, Alagoas, and Rio Grande do Norte relied more on diesel traction, reflected in the emissions from this fossil fuel. Besides CO_2, diesel combustion also emitted fine particles like soot. These particles not only impact air quality but can also absorb solar radiation and affect the climate [59–64]. The burning of diesel also releases nitrogen oxides (NOx), which contribute to the formation of acid rain and tropospheric ozone (a component of smog). Tropospheric ozone is a pollutant and a short-lived greenhouse gas (GHG) [11,65–71].

For the railway systems in the states of Paraiba, Alagoas, and Rio Grande do Norte, which predominantly use diesel traction, the implementation of emission reduction technologies like diesel oxidation catalysts (DOC) and selective catalytic reduction (SCR) systems help minimize NOx and particulate emissions [34,65,72–75]. More efficient engines and fuels with lower sulfur content also contribute to emissions reduction [65,71,76–80], as does transitioning to cleaner energy sources such as electrification (electric vehicles), renewable fuels like biodiesel [13,79,80], and hydrogen technologies [81–84]. In other words, electrification is essential to reduce the GHG emissions from the railway systems in these states, depending on the primary energetic sources used for producing electricity.

The emissions from station power and lighting are factors to consider in all cities. While these emissions may seem smaller compared to traction emissions, they contribute to the overall emission profile of the region.

The "Logistics" category underscores the importance of the emissions related to the transport of equipment, personnel, and materials needed for railway operation and maintenance. This highlights the relevance of logistic efficiency in reducing total emissions. The energy efficiency of vehicles and the logistics operations used for transporting railway system materials in this region should have a more efficient system to consume less fuel and, thus, emit fewer GHGs per unit of transported load [85,86].

The provided data on the greenhouse gas (GHG) emissions in tons of CO_2e from the diesel traction in different railway states in the northeast—Paraiba, Alagoas, Rio Grande do Norte, and Pernambuco, as shown in Figure 5—are essential for understanding the environmental impact of these transportation systems and can serve as a basis for formulating more effective environmental policies in the railway transportation systems of these regions [87–89].

The quantities of the GHG emissions associated with diesel traction vary significantly among the mentioned states. Pernambuco has the highest emissions (578.971 metric tons of CO_2e) followed by Alagoas (554.797 metric tons of CO_2e), Rio Grande do Norte (498.887 metric tons of CO_2e), and Paraiba (346.091 metric tons of CO_2e). This variation is influenced by various factors, such as the length of the routes, where Paraiba has a longer route than the other regions, and the volume of railway traffic, which is higher in Pernambuco due to its status as a major metropolitan area in Northeast Brazil. The energy efficiency of the trains is not a factor since all the light rail vehicles used in this region have the same technology and were manufactured by the same factory. An important factor that could also lead to higher emissions between states is the topography of the region; factors like curves and inclines, among others, could increase GHG emissions [89]. However, this work will not conduct an in-depth study of these factors, as this is one of the limitations of this research.

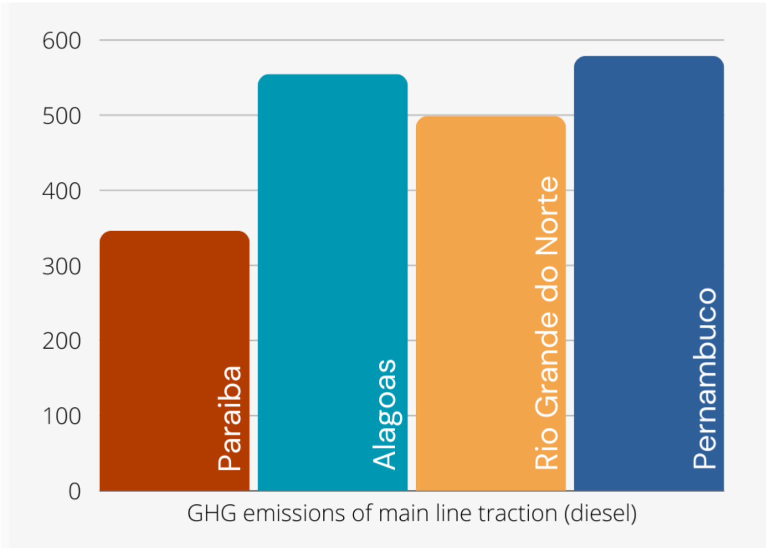

Figure 5. GHG emissions of main line traction (diesel).

3.3. Dismantling and Recycling

Urban railway transportation was developed relatively late in Northeast Brazil, with the opening of the first system in 1985 through repurposing some trains from the existing railway network and the acquisition of new ones. Currently, there is no real data available regarding the dismantling and recycling of urban railway transportation infrastructure in Northeast Brazil. For example, only in 2019 was an industry agreement introduced in Brazil to implement an e-waste reverse logistics system [90]. In addition, there is a compelling need to effectively manage construction and demolition waste due to the limitations of the existing legal framework in Brazil [91]. As a result, dismantling is not discussed in this case study.

The current economy does not incentivize a move towards a more circular economy. However, it is essential to create cleaner and more sustainable rail routes, fully integrated with other environmentally friendly modes of transport. There is clearly a gap in the deployment of supporting infrastructure (such as bridges, tunnels, tracks, yards, electrification, and railway circuits), assets (such as trains, rolling stock, traction systems, locomotives/carriages, and signaling and communication systems) and associated built environments (such as railway stations, mixed-use commercial buildings, and depots), taking into account the concept of the circular economy. According to [4], for this environment to exist, governments/procurement bodies should state that investment decisions will now be made on how circular economic value propositions are thus supporting the concept of circular economic competition. Government intervention should encourage behaviors that support the transition to a circular economy and create a level playing field for transport systems through a rolling strategy that covers short, medium, and long-term goals, grounded in a holistic systems approach [1].

3.4. Limitations

The absence of detailed construction data can hinder the accurate estimation of GHG emissions, 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 [92]. Geographic factors, such as ground softness, can play a crucial role in determining the GHG emissions associated with the earthworks in railway infrastructure construction. The inherent characteristics of products and systems, such as stations, tunnels, and materials like cement (e.g., ready-mix concrete), PHC posts, and steel, often result in their development through unique, one-off projects. Additionally, over 30% of the total GHG emissions from earthworks were linked to the use of equipment such as dump trucks, caterpillar excavators, and tractors, with the emissions heavily influenced by the ground conditions. This approach can lead to outputs with significant variability and uncertainty [25]. The study [93] indicated the increase in emissions and heavy metal in the air, soil, and water in the construction phase of the railway line, but the impacts decreased due to the increase in the utilization ratio of the railway during operation. Landgraf and Horvath [94] studied an analysis based on country-specific supply chains and production processes. Within railway infrastructure, the track (including rails, fasteners, sleepers and ballast) is the main contributor to GHG emissions, comprising 55% of the total in Australia. Furthermore, the carbon footprint of the electrification process depends on the energy mix used to generate electricity. Therefore, it is important to acknowledge that LCA is not limited solely to the construction or operational and maintenance phases; the choice of processes also plays a crucial role in evaluating the environmental impact of railway systems. To address this limitation, researchers can adopt strategies such as tailoring specific cases, conducting within their own defined scopes and system boundaries, using indirect data, modeling, and simulating to estimate the GHG emissions in the construction phase. In this research conducted on the railway system in Pernambuco, the assessment of greenhouse gas emissions (GHG) exclusively focused on the maintenance and operational phases because available studies and databases about construction are missing. 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.

4. Discussion

4.1. Comparative System

This study aims to emphasize the importance of the comparative analysis of traction emissions, station operations, and infrastructure in different urban railway transport systems around the world. It is important to note that the availability of related studies is limited, and the comparative analysis was conducted within the same scope whenever possible, referencing the data and information found in the specialized literature and various case studies with varying local parameters.

In this study, the greenhouse gas (GHG) emissions of the urban railway transport systems in Northeast Brazil, Shanghai Metro, Delhi Metro, and the California corridor (San Diego to Los Angeles, San Francisco, and Sacramento) were compared. Furthermore, the reasons for the differences in data between these regions were explored. To facilitate the comparison, the emission intensities of each city were standardized per passenger–kilometer traveled (PKT).

This comparative analysis allowed for the identification of variations in the GHG emissions among different urban railway transport systems. These differences can be attributed to factors such as the energy source used, the train energy efficiency, the population density, the transport demand profile, and the specific infrastructure of each city. This information is valuable for understanding sustainable transportation practices and policies and can provide insights to enhance efficiency and reduce the emissions in railway systems [18].

By standardizing emission intensities per PKT, fairer comparisons can be made and areas for improvement in each railway system can be identified. This approach considers both the number of passengers transported and the distance traveled, enabling a more equitable assessment of environmental performance [42].

Therefore, this comparison of emissions standardized per PKT in different urban railway systems provides an important view of the disparities and offers valuable information for the development of more sustainable and emission-efficient transportation strategies.

According to [29], in 2012, Shanghai's metro system generated 637,011.3 tCO_2e from electricity consumption for traction. With a total passenger volume of around 2.3 billion and an average travel distance of 12.0 km, the traction emissions amounted to 23.4 g CO_2e per passenger–kilometer traveled (PKT). In the same context, Delhi has a total passenger volume of 651 million passengers and emitted 232,161.7 tCO_2e from traction emissions in 2011, which means 24.3 g CO_2e/PKT. On the other hand, in 2009, the traction emissions of California's high-speed rail system were 31.8 g CO_2e/PKT. It is important to emphasize that this depends on ridership levels. Chester and Horvath, in 2010, reported a range from well under 100 g CO_2e/PKT to over 700 g CO_2e/PKT for the total emissions of the California HSR system, which varied according to the level of travelers. By comparison, Brazil's Northeast system in 2022 had rail transport traction emissions of 9.5 tCO_2e with a total passenger volume of approximately 2,316,000 passengers over an average distance of 194 km with 21.14 gCO_2e/PKT. In 2016, Andrade analyzed the Rio de Janeiro Metro system and calculated emissions of 13.90 g of carbon dioxide per passenger–kilometer traveled [95].

Figure 6 depicts the variation in emissions among the railway transport systems in different world regions. This suggests that factors such as energy source, system efficiency, population density, and other local aspects have a significant impact on the emissions associated with railway transportation.

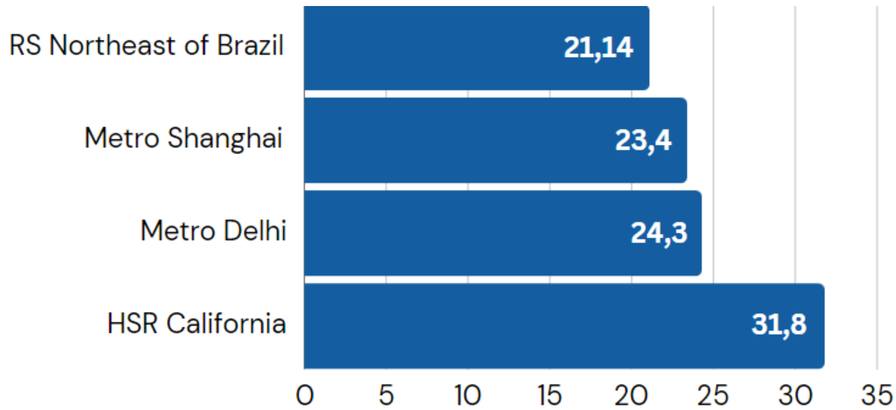

Figure 6. GHG emission (gCO_2/PKT).

The comparison of greenhouse gas (GHG) emissions per passenger–kilometer (gCO_2/PKT) among different railway transport systems provides valuable insights into the environmental efficiency of these systems in different regions of the world [29].

The comparison of the gCO_2/PKT values indicates that metro systems tend to be more emission efficient than light rail systems. This difference can be attributed to the variations in the technology used, the vehicle capacity, and the electrification systems, such as the use of fossil energy for traction in certain trains, as in the case of Northeast Brazil.

It is interesting to note that despite regional differences, the Delhi and Shanghai metro systems exhibit similar gCO_2/PKT values. This might suggest that both systems are adopting similar strategies to reduce emissions, such as the electrification of the main line traction and the adoption of more efficient technologies.

Additionally, metro systems like Delhi's and Shanghai's, which likely have more extensive electrification systems, present lower emissions. It was possible to consider that while construction generates a greater impact than maintenance to the permanent foundation in some countries, the opposite occurs in Northeast Brazil, because most vehicles are brought in only to be assembled. This makes it clear where efforts must be directed to ensure the reduced source of emissions and impacts. In any case, this study sheds light on the importance of electrification in emissions reduction and promoting sustainability in railway systems.

There are several factors that can influence GHG emissions, such as the number of train cars, the type of traction energy (which can vary based on the country's energy matrix), the infrastructure, urban development, and the geographical characteristics of the region, among others. These factors were not extensively studied in this article, serving as limitations to this research.

The gCO_2/PKT values can also be influenced by the local context, including the availability of renewable energy sources, sustainable transportation policies, and investments in infrastructure.

In addition, to compare the greenhouse gas (GHG) emissions per passenger–kilometer (gCO_2/PKT), the extent to which the speed of the system is comparable to other transport systems should still be questioned. This is due to the fact that the functional unit does not take the temporal dimension into account, which limits the significance of comparing train systems. At higher velocities, higher occupation rates over the same distance can be achieved, varying the levels of infrastructure utilization. For example, Beckert et al. [96] suggest changing the functional unit from PKT to PKT/h to make the other systems more comparable.

4.2. Mitigation of GHG Emissions

The mitigation of greenhouse gas (GHG) emissions in the railway system is a topic of great relevance in the context of environmental concerns and emission reduction goals. Based on recently published articles, several promising approaches and strategies to mitigate GHG emissions in the railway sector can be observed.

The electrification of railway lines has been highlighted as one of the main strategies to reduce GHG emissions [20,97]. In the case of the railway system in Northeast Brazil, which consists of both electric and diesel parts, transitioning diesel-powered trains to electric trains powered by renewable energy sources such as solar energy, installed on train rooftops to reduce traction electric energy consumption [10], or the use of wind energy have demonstrated effectiveness in significantly reducing carbon emissions. Additionally, the use of batteries and energy storage systems can enable the use of clean energy even on non-electrified sections [5–9].

The research and development of technologies that improve train efficiency can directly result in GHG emission reduction. Lighter trains [33,98], aerodynamic designs, and energy recovery systems [8,9,99] can minimize fuel consumption and, consequently, carbon emissions.

The implementation of intelligent traffic and operation management systems [100] can optimize train flow, reducing the need for sudden stops and accelerations. This not only saves energy but also contributes to more efficient and lower-emission operations.

Investments in the maintenance and modernization of railway infrastructure can result in smoother tracks, reducing train friction and energy consumption, or even utilizing friction for energy recycling [101–104]. Additionally, modernizing stations and signaling systems can improve operational efficiency [86,105]. The railway sector has a favorable impact on connectivity, saving time and influencing economic and social aspects. The railway system offers highly efficient solutions for densely populated and congested urban areas such as São Paulo. Investing in rail transport is essential for quality of life, as it reduces the commuting time and makes it easier to transport people from regions with lower property costs to areas characterized by limited land area and high population density. Programs promoting the use of these systems are fundamental, since increasing the number of passengers reduces the emissions calculated by life cycle analysis (LCA). However, robust and coordinated investment in transport infrastructure is necessary, as accessibility increases when the system is comprehensive and affordable.

Integration between different modes of transportation, such as rail, buses, and bicycles, can reduce the dependency on private vehicles and, consequently, GHG emissions.

Urban planning focused on accessibility, such as research evaluating the accessibility in high-speed metro systems and light rail vehicles with wheelchair accessibility in public transport, can encourage more people to adopt low-emission transportation modes [106–112].

If Brazil is to expand the rail system, optimize existing infrastructure and target future public investments efficiently, it will need a coordinated strategy that connects states with relevant economic ties. The iron mining sector in Brazil already makes extensive use of this type of transport, and other sectors could be incorporated. The predominance of the road system for heavy transport is a reality, but with the economy growth, the current system will be saturated and new investments will make the rail sector an important alternative, especially if electrified.

The adoption of emission reduction technologies, such as exhaust gas purification systems and particle filters, can contribute to the reduction in emissions in diesel-powered trains. These technologies can minimize the emission of harmful air pollutants.

Empowering operators and maintenance personnel with sustainable and efficient practices can also contribute to emission reduction [113]. Economical driving techniques and proper train maintenance can optimize energy consumption [23].

Finally, it is crucial to ensure that rail network construction and maintenance projects comply with all the applicable environmental requirements, minimizing impacts on the environment. Policies that consider the use of sustainable materials and the recycling of waste should be implemented. The government and future projects need to focus on the importance of recycling routes, the promotion of a circular economy, and the use of sustainable sources of materials, especially those considered critical and strategic.

5. Conclusions

This research aimed to calculate greenhouse gas (GHG) emissions through a life cycle analysis of the railway system in Northeast Brazil. Additionally, a comparative analysis was conducted to the global context to understand the emission levels of urban railway transport systems worldwide. This analysis also aimed to provide guidance for future emission reduction efforts.

The results obtained revealed that the total GHG emissions over the life cycle, considering the construction length of the entire railway system in Northeast Brazil, were 11,996.11 metric tons of CO_2 equivalent (tCO_2e).

The Brazilian urban railway system differs from the rest of the world, as a significant portion of the system is still diesel-powered. The quantities of GHG emissions associated with diesel traction vary significantly among the mentioned states, where Paraiba has the greatest contribution. Nevertheless, when comparing the operation and maintenance phase emissions, the traction emissions of the Brazilian Northeast system were 21.14 gCO_2e/PKT, which were competitive with those of the Delhi Metro and the California high-speed rail corridor, based on a much larger passenger volume in Shanghai. However, there was still significant potential for energy savings in the operation phase, especially in the stations designed to be excessively grandiose and ornamented with energy-intensive facilities. A more reasonable ventilation structure for metro stations and energy-saving lighting, such as LED lights, can effectively reduce their emissions.

These results provide an important understanding of the GHG emissions of the railway system in Northeast Brazil and serve as a basis for identifying the areas for improvement and guiding future actions towards reducing GHG emissions in this context. The analysis of such data can serve as a basis for formulating more effective environmental policies in the railway transport systems of these regions. An awareness of the predominant emission sources in each city can guide the efforts to mitigate environmental impact.

Data like these can highlight the importance of transitioning to cleaner energy sources, such as electric railway traction, low-carbon biofuels, photovoltaic energy, improvements in railway infrastructure, and sustainable stations to reduce the environmental impact of railway transport.

The railway sector, as part of the transportation sector, plays a significant role in meeting the environmental and emissions reduction targets set by various governments and international agreements. However, the railway supply chain is not incentivized to work towards a circular economy. An awareness of the emissions associated with diesel traction is crucial to guide sustainability policies and efforts.

Furthermore, the development of a more comprehensive estimation tool and an applicable reference standard for various areas, equipment types, structures, and techniques would be highly beneficial. This would facilitate the collection and analysis of consistent and comparable data, enabling a more accurate assessment of the GHG emissions in different railway systems.

In summary, the analysis of GHG emissions data in railways provides valuable insights for sustainability-oriented decision-making. These insights can steer investments towards cleaner technologies, efficient transportation strategies, and collaborations between the public and private sectors to achieve environmental goals and reduce the carbon footprint of railway transport.

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References

1. Kaewunruen, S.; Sresakoolchai, J.; Peng, J. Life cycle cost, energy and carbon assessments of Beijing-Shanghai high-speed railway. *Sustainability* **2020**, *12*, 206. [CrossRef]
2. Lin, J.; Li, H.; Huang, W.; Xu, W.; Cheng, S. A Carbon Footprint of High-Speed Railways in China: A Case Study of the Beijing-Shanghai Line. *J. Ind. Ecol.* **2019**, *23*, 869–878. [CrossRef]
3. Shi, X.Y.; Qiao, X.Q.; Ni, J.M.; Zheng, Y.Y. Experimental and CFD study on combustion noise and pollutant emissions of diesel engine with split injections of common rail system. *Shanghai Jiaotong Daxue Xuebao/J. Shanghai Jiaotong Univ.* **2010**, *44*, 1566–1572.
4. Trevisan, L.; Bordignon, M. Screening Life Cycle Assessment to compare CO_2 and Greenhouse Gases emissions of air, road, and rail transport: An exploratory study. *Procedia CIRP* **2020**, *90*, 303–309. [CrossRef]
5. Gee, A.M.; Dunn, R.W. Analysis of Trackside Flywheel Energy Storage in Light Rail Systems. *IEEE Trans. Veh. Technol.* **2015**, *64*, 3858–3869. [CrossRef]
6. Zhu, F.; Yang, Z.; Lin, F.; Xin, Y. Decentralized Cooperative Control of Multiple Energy Storage Systems in Urban Railway Based on Multiagent Deep Reinforcement Learning. *IEEE Trans. Power Electron.* **2020**, *35*, 9368–9379. [CrossRef]
7. Khodaparastan, M.; Dutta, O.; Saleh, M.; Mohamed, A.A. Modeling and Simulation of DC Electric Rail Transit Systems With Wayside Energy Storage. *IEEE Trans. Veh. Technol.* **2019**, *68*, 2218–2228. [CrossRef]
8. Zhu, F.; Yang, Z.; Zhao, Z.; Lin, F. Two-Stage Synthetic Optimization of Supercapacitor-Based Energy Storage Systems, Traction Power Parameters and Train Operation in Urban Rail Transit. *IEEE Trans. Veh. Technol.* **2021**, *70*, 8590–8605. [CrossRef]
9. Krueger, H.; Fletcher, D.; Cruden, A. Vehicle-to-Grid (V2G) as line-side energy storage for support of DC-powered electric railway systems. *J. Rail Transp. Plan. Manag.* **2021**, *19*, 100263. [CrossRef]
10. Carneiro, M.A.; Soares, D.D.F. Solar photovoltaic assistance system study for a Brazilian light rail vehicle. *U.Porto J. Eng.* **2020**, *6*, 35–45. [CrossRef]
11. Zare, A.; Stevanovic, S.; Jafari, M.; Verma, P.; Babaie, M.; Yang, L.; Rahman, M.M.; Ristovski, Z.D.; Brown, R.J.; Bodisco, T.A. Analysis of cold-start NO_2 and NOx emissions, and the NO_2/NOx ratio in a diesel engine powered with different diesel-biodiesel blends. *Environ. Pollut.* **2021**, *290*, 118052. [CrossRef] [PubMed]
12. Kurczyński, D. Effect of the rme biodiesel on the diesel engine fuel consumption and emission. *Commun. Sci. Lett. Univ. Zilina* **2021**, *23*, B308–B316. [CrossRef]

13. Thongchai, S.; Lim, O. Macroscopic spray behavior of a single-hole common rail diesel injector using gasoline-blended 5% biodiesel. *Energies* **2020**, *13*, 2276. [CrossRef]
14. Li, F.; Lin, Q. Radial development of pentanol-biodiesel fuel spray in a high-pressure common-rail system. *Phys. Fluids* **2021**, *33*, 095115. [CrossRef]
15. Zhu, H.Y.; Fang, J.H.; Zhang, W.G.; Huang, Z. Spray characteristics of biodiesel within a common rail system. *K. Cheng Je Wu Li Hsueh Pao/J. Eng. Thermophys.* **2011**, *32*, 1785–1788.
16. Aminzadegan, S.; Shahriari, M.; Mehranfar, F.; Abramović, B. Factors affecting the emission of pollutants in different types of transportation: A literature review. *Energy Rep.* **2022**, *8*, 2508–2529. [CrossRef]
17. Chen, Z. Socioeconomic Impacts of high-speed rail: A bibliometric analysis. *Socio-Econ. Plan. Sci.* **2022**, *85*, 101265. [CrossRef]
18. Da Fonseca-Soares, D.; Eliziário, S.A.; Galvinicio, J.D.; Ramos-Ridao, A.F. Life-Cycle Greenhouse Gas (GHG) Emissions Calculation for Urban Rail Transit Systems: The Case of Pernambuco Metro. *Appl. Sci.* **2023**, *13*, 8965. [CrossRef]
19. Gulcimen, S.; Aydogan, E.K.; Uzal, N. Life cycle sustainability assessment of a light rail transit system: Integration of environmental, economic, and social impacts. *Integr. Environ. Assess. Manag.* **2021**, *17*, 1070–1082. [CrossRef]
20. Ramos da Silva, T.; Moura, B.; Monteiro, H. Life Cycle Assessment of Current Portuguese Railway and Future Decarbonization Scenarios. *Sustainability* **2023**, *15*, 11355. [CrossRef]
21. Hausberger, L.; Cordes, T.; Gschösser, F. Life Cycle Assessment of High-Performance Railway Infrastructure, Analysis of Superstructures in Tunnels and on Open Tracks. *Sustainability* **2023**, *15*, 7064. [CrossRef]
22. Keiser, D.; Schnoor, L.H.; Pupkes, B.; Freitag, M. Life cycle assessment in aviation: A systematic literature review of applications, methodological approaches and challenges. *J. Air Transp. Manag.* **2023**, *110*, 102418. [CrossRef]
23. Merchan, A.L.; Belboom, S.; Léonard, A. Life cycle assessment of rail freight transport in Belgium. *Clean Technol. Environ. Policy* **2020**, *22*, 1109–1131. [CrossRef]
24. Gebler, M.; Cerdas, J.F.; Thiede, S.; Herrmann, C. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production—A case study. *J. Clean. Prod.* **2020**, *270*, 122330. [CrossRef]
25. Lee, J.Y.; Lee, C.K.; Chun, Y.Y. Greenhouse gas emissions from high-speed rail infrastructure construction in Korea. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102514. [CrossRef]
26. Da Fonseca-Soares, D.; Galvinicio, J.D.; Eliziário, S.A.; Ramos-Ridao, A.F. A Bibliometric Analysis of the Trends and Characteristics of Railway Research. *Sustainability* **2022**, *14*, 13956. [CrossRef]
27. Thondoo, M.; Marquet, O.; Márquez, S.; Nieuwenhuijsen, M.J. Small cities, big needs: Urban transport planning in cities of developing countries. *J. Transp. Health* **2020**, *19*, 100944. [CrossRef]
28. Hamurcu, M.; Eren, T. Strategic planning based on sustainability for urban transportation: An application to decision-making. *Sustainability* **2020**, *12*, 3589. [CrossRef]
29. Li, Y.; He, Q.; Luo, X.; Zhang, Y.R.; Dong, L. Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro. *Resour. Conserv. Recycl.* **2018**, *128*, 451–457. [CrossRef]
30. Chang, T.; Yang, D.; Yang, Y.; Huo, J.; Wang, G.; Xiong, C. Impact of urban rail transit on business districts based on time distance: Urumqi light rail. *J. Urban Plan. Dev.* **2018**, *144*, 04018024. [CrossRef]
31. Lazzerini, G.; Lucchetti, S.; Nicese, F.P. Green House Gases(GHG) emissions from the ornamental plant nursery industry: A Life Cycle Assessment(LCA) approach in a nursery district in central Italy. *J. Clean. Prod.* **2016**, *112*, 4022–4030. [CrossRef]
32. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006; pp. 1–20.
33. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006; pp. 1–46.
34. *SimaPro*, Version 8.4.1; PRe Sustainability: Amersfoort, The Netherlands, 2018. Available online: https://support.simapro.com/s/ (accessed on 12 March 2022).
35. Liljenstrom, C.; Toller, S.; Akerman, J.; Bjorklund, A. Annual climate impact and primary energy use of Swedish transport infrastructure. *Eur. J. Transp. Infrastruct. Res.* **2019**, *19*, 77–116. [CrossRef]
36. Kimball, M.; Chester, M.; Gino, C.; Reyna, J. Assessing the Potential for Reducing Life-Cycle Environmental Impacts through Transit-Oriented Development Infill along Existing Light Rail in Phoenix. *J. Plan. Educ. Res.* **2013**, *33*, 395–410. [CrossRef]
37. Puig-Samper Naranjo, G.; Bolonio, D.; Ortega, M.F.; García-Martínez, M.-J. Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. *J. Clean. Prod.* **2021**, *291*, 125883. [CrossRef]
38. Olugbenga, O.; Kalyviotis, N.; Saxe, S. Embodied emissions in rail infrastructure: A critical literature review. *Environ. Res. Lett.* **2019**, *14*, 21. [CrossRef]
39. WRI Brasil. Greenhouse gas protocol calculation tool for forestry in Brazil. Technical note. Janeiro de 2020. 32p. Available online: https://wribrasil.org.br/sites/default/files/ghg_protocolo-florestastechnicalnote.pdf (accessed on 23 November 2024).
40. Giunta, M.; Leonardi, G. Framework for Life Cycle Railway Sustainability Assessment: A Methodological Approach Based on Advanced Methods and Tools. In Proceedings of the Computational Science and Its Applications—ICCSA 2024 Workshops, Hanoi, Vietnam, 1–4 July 2024; pp. 233–244.
41. Rempelos, G.; Preston, J.; Blainey, S. A carbon footprint analysis of railway sleepers in the United Kingdom. *Transp. Res. Part D Transp. Environ.* **2020**, *81*, 24. [CrossRef]

42. Chang, Y.; Lei, S.H.; Teng, J.J.; Zhang, J.X.; Zhang, L.X.; Xu, X. The energy use and environmental emissions of high-speed rail transportation in China: A bottom-up modeling. *Energy* **2019**, *182*, 1193–1201. [CrossRef]
43. Wang, L.; Jiao, G.H.; Lu, H.S.; Wang, Q.Q.; IOP. Environmental Load of Iron Ore Transportation, Bayan Obo Mine, China. In Proceedings of the International Conference on Air Pollution and Environmental Engineering (APEE), Hong Kong, China, 26–28 October 2018.
44. Zhang, H.; Li, S.; Wang, Z.; Li, M.; Yu, C.; Ren, S.; Sun, K.; Li, G.; Wang, J. Emission performance of gasoline homogeneous charge induced ignition in multi-cylinder diesel engine. *Nongye Gongcheng Xuebao/Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 108–114.
45. EPA. Greenhouse Gas Inventory Guidance: Direct Emissions from Mobile Combustion Source. 2020. Available online: https://www.epa.gov/sites/default/files/2020-12/documents/mobileemissions.pdf (accessed on 13 August 2023).
46. Banar, M.; Özdemir, A. An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. *Transp. Res. Part D Transp. Environ.* **2015**, *41*, 88–105. [CrossRef]
47. Pons, J.J.; Villalba Sanchis, I.; Insa Franco, R.; Yepes, V. Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks. *Environ. Impact Assess. Rev.* **2020**, *85*, 106444. [CrossRef]
48. Iyer, K.; Wennhagea, P.; Åkermo, M. Life-cycle Assessment of a Composite Railway bogie frame. *Procedia CIRP* **2024**, *122*, 988–993. [CrossRef]
49. Soleimani-Chamkhorami, K.; Garmabaki, A.H.S.; Kasraei, A.; Famurewa, S.M.; Odelius, J.; Strandberg, G. Life cycle cost assessment of railways infrastructure asset under climate change impacts. *Transp. Res. Part D Transp. Environ.* **2024**, *127*, 104072. [CrossRef]
50. Chang, B.; Kendall, A. Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system. *Transp. Res. Part D Transp. Environ.* **2011**, *16*, 429–434. [CrossRef]
51. Montoya-Torres, J.; Akizu-Gardoki, O.; Iturrondobeitia, M. Measuring life-cycle carbon emissions of private transportation in urban and rural settings. *Sustain. Cities Soc.* **2023**, *96*, 104658. [CrossRef]
52. MCTI. Ministério da Ciência, Tecnologia e Inovação: Fatores de emissão de CO2 pela geração de energia elétrica no Sistema Interligado Nacional do Brasil—Ano Base 2019. Available online: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/dados-e-ferramentas/fatores-de-emissao (accessed on 12 March 2022).
53. Disney, J.; Rossiter, W.; Smith, D.J. Nottingham Express Transit: The role of green innovation in the drive for sustainable mobility through improved public transport. *Int. J. Entrep. Innov.* **2018**, *19*, 56–68. [CrossRef]
54. Bates, T.B.; Jablonski, P. San Diego, California, Trolley's new green line: Early success for distinctive service. *Transp. Res. Rec.* **2007**, *2006*, 40–49. [CrossRef]
55. Qi, Y.Y.; Dai, H.Y.; Gao, H.; Gan, F. Dynamic analysis of high-speed train with considering drive system. *Zhendong Gongcheng Xuebao/J. Vib. Eng.* **2019**, *32*, 176–183.
56. Chu, W.J.; Zhang, X.C.; Chen, J.H.; Xu, B. An ELM-Based Approach for Estimating Train Dwell Time in Urban Rail Traffic. *Math. Probl. Eng.* **2015**, *2015*, 473432. [CrossRef]
57. Jackson, D.J.; Brander, M. The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector. *J. Clean. Prod.* **2019**, *223*, 739–746. [CrossRef]
58. Mao, J.; Xiang, J.; Yu, C.; Liu, X.; Gong, K. Wear and stability analysis of the train-curve rail system with an elastic anti-friction guard rail. *Dyna* **2015**, *90*, 532–539. [CrossRef]
59. Fan, L.; Bai, Y.; Ma, X.; Song, E. Analysis upon fuel injection quantity variation of common rail system for diesel engines. *J. Mech. Sci. Technol.* **2016**, *30*, 3365–3377. [CrossRef]
60. Li, Q.; Backes, F.; Wachtmeister, G. Application of canola oil operation in a diesel engine with common rail system. *Fuel* **2015**, *159*, 141–149. [CrossRef]
61. Shao, L.M.; An, S.J.; Chang, H.B. Calculation and analysis of combustion and emission of a diesel engine with high pressure common rail system. *Neiranji Gongcheng/Chin. Intern. Combust. Engine Eng.* **2005**, *26*, 1–4.
62. Zhang, Z.; Zhao, F.; Deng, J.; Li, L.; Shen, Y. Characteristics of the multiple injection diesel spray employed common rail system. *J. Therm. Sci. Technol.* **2013**, *8*, 106–119. [CrossRef]
63. Kuti, O.A.; Zhu, J.; Nishida, K.; Wang, X.; Huang, Z. Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system. *Fuel* **2013**, *104*, 838–846. [CrossRef]
64. Zheng, J.B.; Miao, X.L.; Hong, J.H.; Wang, X.Y.; Chen, X.Y.; Ju, Y.S.; Bi, F.Y. Combustion delay of premixed combustion in diesel engine. *Neiranji Xuebao/Trans. CSICE (Chin. Soc. Intern. Combust. Engines)* **2011**, *29*, 241–247.
65. Mohamed Ibrahim, M.; Varuna Narasimhan, J.; Ramesh, A. Comparison of the predominantly premixed charge compression ignition and the dual fuel modes of operation with biogas and diesel as fuels. *Energy* **2015**, *89*, 990–1000. [CrossRef]
66. Krasinski, A.; Gradon, L. Comprehensive system for diesel fuel cleaning. *Filtr. Sep.* **2016**, *53*, 33–36. [CrossRef]
67. Liu, L.; Yang, F.Y.; Ouyang, M.G.; Fang, C.; Jiang, Z.J.; Hao, S.G. Control and optimization of diesel/LNG system of a 4G200 diesel engine. *Jilin Daxue Xuebao (Gongxueban)/J. Jilin Univ. (Eng. Technol. Ed.)* **2015**, *45*, 414–419.
68. Alcántara-Carmona, A.; Sáez-Bastante, J.; Dorado, M.P. Corrosion testing of a diesel engine common rail system using various types of biodiesel. *Renew. Energy Power Qual. J.* **2017**, *1*, 427–432. [CrossRef]
69. Song, G.; Li, J.; Hu, L.; Jiang, Z. Development of magnetoelectric speed sensor for high pressure common rail system. *Yi Qi Yi Biao Xue Bao/Chin. J. Sci. Instrum.* **2006**, *27*, 290–294.

70. Ferrari, A.; Salvo, E. Determination of the transfer function between the injected flow-rate and high-pressure time histories for improved control of common rail diesel engines. *Int. J. Engine Res.* **2017**, *18*, 212–225. [CrossRef]
71. Gong, W.G.; Lou, J.P.; Ping, Y.S.; Zhu, G.H.; Wang, Q. Development and application of Model D19 Diesel Engine for passenger car. *Neiranji Gongcheng/Chin. Intern. Combust. Engine Eng.* **2013**, *34*, 5–12.
72. Donnici, G.; Rocchi, I.; Pezzuti, E. Aircraft diesel engine turbocompound optimized. *Far East J. Electron. Commun.* **2014**, *13*, 137–154.
73. Shin, J.; Hong, S.; Park, I.; Sunwoo, M. Common rail pressure control algorithm for passenger car diesel engines using quantitative feedback theory. *Trans. Korean Soc. Mech. Eng. B* **2014**, *38*, 107–114. [CrossRef]
74. Li, F.; Fu, W.; Yi, B.; Song, L.; Liu, T.; Wang, X.; Wang, C.; Lei, Y.; Lin, Q. Comparison of macroscopic spray characteristics between biodiesel-pentanol blends and diesel. *Exp. Therm. Fluid Sci.* **2018**, *98*, 523–533. [CrossRef]
75. Zhang, X.; Wei, J.; Lü, G.; Song, C. A Comparison of Number and Size Distribution and Mass of Particulates for Biodiesel and Diesel in Post-Injection Combustion Process. *Ranshao Kexue Yu Jishu/J. Combust. Sci. Technol.* **2017**, *23*, 261–267.
76. Ferrari, A.; Novara, C.; Paolucci, E.; Vento, O.; Violante, M.; Zhang, T. Design and rapid prototyping of a closed-loop control strategy of the injected mass for the reduction of CO_2, combustion noise and pollutant emissions in diesel engines. *Appl. Energy* **2018**, *232*, 358–367. [CrossRef]
77. Liu, X.; Zhang, H.M.; Ji, L.W.; Li, S.A. Development of common rail system and performance researching of electronic-controlled diesel engine. *Neiranji Gongcheng/Chin. Intern. Combust. Engine Eng.* **2005**, *26*, 1–5.
78. Matsumoto, K. Development of diesel common rail system and production Technology. *Seimitsu Kogaku Kaishi/J. Jpn. Soc. Precis. Eng.* **2009**, *75*, 140–141. [CrossRef]
79. Thongchai, S.; Lim, O. Investigation of the combustion characteristics of gasoline compression ignition engine fueled with gasoline-biodiesel blends. *J. Mech. Sci. Technol.* **2018**, *32*, 959–967. [CrossRef]
80. Vargas, F.; Pérez, A.; Delgado, R.; Hernández, E.; Suástegui, J.A. Performance analysis of a compression ignition engine using mixture biodiesel palm and diesel. *Sustainability* **2019**, *11*, 4918. [CrossRef]
81. Fang, W.; Huang, B.; Kittelson, D.B.; Northrop, W.F. Dual-Fuel diesel engine combustion with hydrogen, gasoline, and ethanol as fumigants: Effect of diesel injection timing. *J. Eng. Gas Turbines Power* **2014**, *136*, 081502. [CrossRef]
82. Fernández-Ríos, A.; Santos, G.; Pinedo, J.; Santos, E.; Ruiz-Salmón, I.; Laso, J.; Lyne, A.; Ortiz, A.; Ortiz, I.; Irabien, Á.; et al. Environmental sustainability of alternative marine propulsion technologies powered by hydrogen—A life cycle assessment approach. *Sci. Total Environ.* **2022**, *820*, 153189. [CrossRef] [PubMed]
83. Ibrahim, M.M.; Ramesh, A. Experimental investigations on a hydrogen diesel homogeneous charge compression ignition engine with exhaust gas recirculation. *Int. J. Hydrogen Energy* **2013**, *38*, 10116–10125. [CrossRef]
84. Ciancetta, F.; Ometto, A.; D'ovidio, G.; Masciovecchio, C. Modeling, Analysis and Implementation of an Urban Electric Light-Rail Train Hydrogen Powered. *Int. Rev. Electr. Eng.* **2019**, *14*, 237–245. [CrossRef]
85. Okyere, S.; Yang, J.; Aminatou, M.; Tuo, G.; Zhan, B. Multimodal transport system effect on logistics responsive performance: Application of ordinal logistic regression. *Eur. Transp. Trasp. Eur.* **2018**, *68*, 1–17.
86. Perez-Martinez, P.J.; Miranda, R.M.; Andrade, M.F. Freight road transport analysis in the metro Sao Paulo: Logistical activities and CO_2 emissions. *Transp. Res. Part A Policy Pract.* **2020**, *137*, 16–33. [CrossRef]
87. Holler Branco, J.E.; Bartholomeu, D.B.; Alves Junior, P.N.; Caixeta Filho, J.V. Evaluation of the economic and environmental impacts from the addition of new railways to the brazilian's transportation network: An application of a network equilibrium model. *Transp. Policy* **2022**, *124*, 61–69. [CrossRef]
88. Holian, M.J.; Kahn, M.E. Household demand for low carbon policies: Evidence from california. *J. Assoc. Environ. Resour. Econ.* **2015**, *2*, 205–234. [CrossRef]
89. Wen, L.; Wang, A. System dynamics model of Beijing urban public transport carbon emissions based on carbon neutrality target. *Environ. Dev. Sustain.* **2022**, *25*, 12681–12706. [CrossRef]
90. Dias, P.; Palomero, J.; Cenci, M.P.; Scarazzato, T.; Bernardes, A.M. Electronic waste in Brazil: Generation, collection, recycling and the covid pandemic. *Cleaner Waste Systems* **2022**, *3*, 100022. [CrossRef]
91. Brandao, R.; Edwards, D.J.; Melo, A.C.S.; Macedo, A.N. Reverse supply chain practices for construction and demolition waste in the Brazilian Amazon: A multi-stakeholder view. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 2245–2261. [CrossRef]
92. Ingrao, C.; Scrucca, F.; Matarazzo, A.; Arcidiacono, C.; Zabaniotou, A. Freight transport in the context of industrial ecology and sustainability: Evaluation of uni-and multi-modality scenarios via life cycle assessment. *Int J Life Cycle Assess* **2021**, *26*, 127–142. [CrossRef]
93. Bilgili, L.; Kuzu, S.L.; Çetinkaya, A.Y.; Kumar, P. Evaluation of railway versus highway emissions using LCA approach between the two cities of Middle Anatolia. *Sustain. Cities Soc.* **2019**, *49*, 101635. [CrossRef]
94. Landgraf, M.; Horvath, A. Embodied greenhouse gas assessment of railway infrastructure: The case of Austria. *Environ. Res. Infrastruct. Sustain.* **2021**, *1*, 025008. [CrossRef]
95. De Andrade, C.E.S.; D'Agosto, M.A. Energy use and carbon dioxide emissions assessment in the lifecycle of passenger rail systems: The case of the Rio de Janeiro Metro. *J. Clean. Prod.* **2016**, *126*, 526–536. [CrossRef]
96. Beckert, P.; Pareschi, G.; Ehwald, J.; Sacchi, R.; Bauer, C. Fast as a plane, clean as a train? Prospective life cycle assessment of a hyperloop system. *Resour. Environ. Sustain.* **2024**, *17*, 100162. [CrossRef]

97. Chen, L.; Jung, J.; Sohn, G. Multi-Scale Hierarchical CRF for Railway Electrification Asset Classification from Mobile Laser Scanning Data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2019**, *12*, 3131–3148. [CrossRef]
98. Dalkic, G.; Balaban, O.; Tuydes-Yaman, H.; Celikkol-Kocak, T. An assessment of the CO_2 emissions reduction in high speed rail lines: Two case studies from Turkey. *J. Clean. Prod.* **2017**, *165*, 746–761. [CrossRef]
99. Soffker, C.; Gralla, C. "Smart" power supply for urban rail systems thanks to Hesop. *Elektr. Bahnen* **2016**, *114*, 10–16.
100. Masirin, M.I.M.; Salin, A.M.; Zainorabidin, A.; Martin, D.; Samsuddin, N. Review on Malaysian Rail Transit Operation and Management System: Issues and Solution in Integration. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *226*, 012029. [CrossRef]
101. Mayba, I.A.; Glazunov, D.V. Optimization of Tribotechnical Characteristics of Wheel–Rail Friction Modifiers. *J. Frict. Wear* **2020**, *41*, 517–520. [CrossRef]
102. Gerlici, J.; Gorbunov, M.; Kravchenko, K.; Domin, R.; Kovtanets, M.; Lack, T. Slipping and Skidding Occurrence Probability Decreasing by Means of the Friction Controlling in the Wheel-Braking Pad and Wheel-Rail Contacts. *Manuf. Technol.* **2017**, *17*, 17–18. [CrossRef]
103. Cui, X.; He, Z.; Huang, B.; Chen, Y.; Du, Z.; Qi, W. Study on the effects of wheel-rail friction self-excited vibration and feedback vibration of corrugated irregularity on rail corrugation. *Wear* **2021**, *477*, 203854. [CrossRef]
104. Sánchez, J.C.; Jaramillo, J.A.; Santa, J.F.; Toro, A. Twin-disc assessment of the effect of top-of-rail friction modifiers on the tribological response of er8-r370ht pairs for use in wheel-rail systems. *Rev. Latinoam. Metal. Mater.* **2019**, *39*, 2–15.
105. Gassner, A.; Lederer, J.; Kanitschar, G.; Ossberger, M.; Fellner, J. Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria. *Land Use Policy* **2018**, *72*, 85–99. [CrossRef]
106. Yao, E.; Cheng, X.; Liu, S.; Zhang, R. Accessibility-based forecast on passenger flow entering and departing existing urban railway stations. *Tiedao Xuebao/J. China Railw. Soc.* **2016**, *38*, 1–7.
107. Bonotti, R.; Rossetti, S.; Tiboni, M.; Tira, M. Analysing Space-Time Accessibility Towards the Implementation of the Light Rail System: The Case Study of Brescia. *Plan. Pract. Res.* **2015**, *30*, 424–442. [CrossRef]
108. Moyano, A.; Martínez, H.S.; Coronado, J.M. From network to services: A comparative accessibility analysis of the Spanish high-speed rail system. *Transp. Policy* **2018**, *63*, 51–60. [CrossRef]
109. Liu, Z.; Zhu, A.X.; Zhang, W.; Ren, M. An improved potential-based approach to measuring the daily accessibility of HSR. *Transp. Res. Part A Policy Pract.* **2021**, *150*, 271–284. [CrossRef]
110. Janic, M. Light rail rapid transit systems for more sustainable ground accessibility of airports. *Transp. Plan. Technol.* **2011**, *34*, 569–592. [CrossRef]
111. Hong, L.; Ouyang, M.; Xu, M.; Hu, P. Time-varied accessibility and vulnerability analysis of integrated metro and high-speed rail systems. *Reliab. Eng. Syst. Saf.* **2020**, *193*, 106622. [CrossRef]
112. Ferreira, A.F.; Leite, A.D.; Pereira, L.D.F.; Neves, J.M.D.J.; Oliveira Pinheiro, M.G.D.; Chang, S.K.J. Wheelchair accessibility of urban rail systems: Some preliminary findings of a global overview. *IATSS Res.* **2021**, *45*, 326–335. [CrossRef]
113. Carneiro, M.A.; Da Fonseca-Soares, D.; Pereira, L.H.M.; Ramos-Ridao, A.F. An Approach for Water and Energy Savings in Public Buildings: A Case Study of Brazilian Rail Company. *Sustainability* **2022**, *14*, 15921. [CrossRef]