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Analysis of Carbon Footprint into Railway Superstructures; Ballasted and Slab Tracks

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ABSTRACT

Global warming is being accelerated by rising greenhouse gas emissions from human activity, which carries serious repercussions for long-term sustainability. Of these gases, carbon dioxide (CO_2) is the most critical driver of climate change. Railway construction and maintenance, in particular, demand vast quantities of materials, making the sector a notable source of CO_2. To address this, we must implement thorough quantitative assessments and innovative design improvements to lower the industry's environmental cost. This study identifies and quantifies the carbon footprint of two common railway superstructures: ballasted track and slab track. To achieve this aim, a life-cycle assessment was performed in accordance with sustainable design and resilient infrastructure frameworks. Finally, the results were benchmarked against the Carbon Emission Index (CEI) to measure each alternative's deviation from the optimal reference value. The results of this study show that slab track produces higher CO_2 emissions than ballasted track, mainly because of its greater consumption of concrete and reinforcing steel. The total emissions were estimated at 823.87 t CO_2/km for slab track and 498.51 t CO_2/km for ballasted track. The CEI values of 1.62 for slab track and 1.55 for ballasted track further confirm that ballasted track demonstrates better environmental performance. Therefore, from a carbon-emission perspective, ballasted track appears to be the more sustainable railway superstructure.

1. Introduction

The increasing levels of carbon dioxide (CO_2) in the atmosphere have become a major environmental challenge due to their contribution to global warming [1]. The increase in atmospheric CO_2 concentration is largely caused by the combustion of fossil fuels for energy generation, deforestation, and agricultural practices [2]. The Climate Change 2021 report by Working Group of the Intergovernmental Panel on Climate Change (IPCC) emphasizes that approximately 1.1 °C of the increase in global temperature (since the pre-industrial period) is caused by greenhouse gas emissions from human activities [3]. To evaluate the environmental aspect of sustainable development across countries, a calculated value or index called the carbon footprint, derived from the ecological footprint concept proposed by Wackernagel and Rees, has been introduced. Carbon footprint, expressed in CO_2 equivalents, is a method for estimating the greenhouse gas emissions produced throughout a product's entire life cycle [4]. UNEP (United Nations Environment Programme) Emissions Gap Report 2025 cautions that, in the absence of enhanced reduction efforts, general global policies are expected to lead to an increase of 2.8°C in average global temperatures by the end of the century [5]. If greenhouse gas emissions are not

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reduced soon, global temperatures will keep increasing, posing serious threats to ecosystems, sea levels, agriculture, and human society [3]. The burning of fossil fuels is a major source of air pollution in this sector. In 2023, the transport sector was the second-largest contributor to global greenhouse gas emissions, with about 8.4 Gt CO_2-equivalent [5].

According to EPA data, electricity and heat production accounted for about 25% of global GHG emissions, transportation about 15%, industry about 21%, and buildings about 6%–10% [6]. This scenario has highlighted the necessity for an effective transportation system, As the transport sector is responsible for a large share of emissions [7]. the increasing number of vehicles further exacerbates this issue, as all transportation modes rely on road or railway infrastructure and contribute to greenhouse gas emissions throughout their life cycles. To accurately estimate life-cycle greenhouse gas emissions associated with transport modes, it is essential to establish a comprehensive life cycle assessment (LCA) database covering all stages [8]. Kim et al. [9] analyzed greenhouse gas emissions from construction equipment, while Hanson et al. [10] and Shi et al. [11] studied how specific construction materials affect greenhouse gas emissions. Additionally, this researchs have been conducted to assess the greenhouse gas emissions resulting from transportation construction and maintenance. Researchers Yanguk Seo and Sung Min Kim have quantified the carbon dioxide emissions—one of the main greenhouse gases—resulting from material use in the constructions of transportation [12]. In a similar manner, Wiedmann and Minx have explored how human activities, particularly since the Industrial Revolution, have intensified concerns related to the global carbon cycle [13].

Recent studies have increasingly emphasized the importance of evaluating railway infrastructure from a life-cycle perspective. A comprehensive review by Hu et al. [14] showed a rapid growth in railway carbon-emission research, with life cycle assessment (LCA) being one of the most widely used approaches. Similarly, Taeb et al. [15] reviewed 116 case studies and highlighted the significant influence of system boundaries, maintenance assumptions, and inventory data on the estimated global warming potential of railway tracks. Several studies have specifically compared the environmental performance of ballasted and slab track systems. Hausberger et al. [16] demonstrated that service life and renewal cycles strongly affect the environmental impacts of railway superstructures throughout their life cycle. Knabl and Landgraf [17] further showed that subsoil conditions of railway infrastructure can significantly influence greenhouse gas emissions, with more than 80% of emissions originating from material production. In addition, Najafpour Navaei et al. [18] emphasized the need for standardized carbon-footprint assessment methods to improve the consistency and comparability of railway infrastructure studies.

Although previous studies have significantly advanced the understanding of the environmental impacts associated with railway infrastructure, limited research has examined the comparative performance of railway superstructure systems using a unified, benchmark-based carbon metric. Since carbon emissions are intrinsically associated with the production and use of construction materials, their complete elimination is not feasible in practice; consequently, absolute emission values alone are insufficient for evaluating the relative environmental efficiency of alternative track systems. Previous studies have proposed various approaches to environmental and carbon-related performance assessment. Fakher [19] employed the ecological footprint concept to evaluate environmental quality, while Mohsin et al. [20], Chen et al. [21], Mansour and Novak [22], and Mosley [23] developed carbon- and sustainability-related indices for national, regional, policy, laboratory, and construction-sector applications. However, none of these studies addressed the comparative assessment of railway track alternatives using a benchmark-based carbon metric.

To address this gap, the present study proposes a Carbon Emission Index (CEI) as a standardized indicator for quantifying and comparing the environmental performance of alternative track systems by relating actual life-cycle carbon emissions to a low-carbon benchmark. Accordingly, the life-cycle carbon emissions of ballasted and slab track systems are evaluated across the production, construction, operation, and end-of-life phases under both actual and optimal emission scenarios. By integrating these results into a single benchmark-based metric, the proposed framework enables a more comprehensive assessment of railway superstructure performance and provides insight into the potential for further environmental optimization.

2. Research Methodology

The present study was designed to provide a systematic and directly comparable assessment of two representative railway superstructure systems, namely a conventional ballasted track and a ballastless track. For the ballastless alternative, the RHEDA 2000 system was selected as the reference case due to its extensive application in high-speed railway networks and its widespread adoption. Therefore, it provides a suitable basis for representing the slab-track category in a comparative life-cycle assessment. The material composition of each system was identified, and the quantities of all constituent materials required for a functional unit of 1 km of track were determined. Based on these inventories, the life-cycle carbon emissions of both systems were quantified by considering the emissions associated with material production, construction, operation, and end-of-life stages. Although total carbon emissions provide a direct measure of the environmental impact of railway superstructures, their absolute values alone do not adequately reflect the relative environmental efficiency of alternative track systems. Since carbon emissions are inherently associated with the production and use of construction materials, eliminating them entirely is generally impractical. Therefore, a benchmark reference is required to assess whether the calculated emissions represent an environmentally efficient or inefficient solution. Without such a benchmark, the interpretation of total carbon emissions remains limited, particularly when comparing different railway superstructure alternatives.

To establish a meaningful benchmark for comparison, the same material inventories were reassessed using the Low Embodied Carbon (LEC) requirements developed by the U.S. General Services Administration (GSA). Benchmark GWP values were extracted from the published GSA criteria for materials included in the LEC framework, such as concrete, steel, asphalt-related products, and fastening components. For materials not covered by the GSA database, benchmark values were taken from recognized literature sources that were also focused on low-carbon material assessment and were therefore consistent with the GSA approach, ensuring a complete and coherent benchmark dataset. Specifically, the ballast emission factor was adopted from an ISO 14040-based life-cycle assessment, and the bitumen value was obtained from California Department of Transportation recommendations. These benchmark values were then applied to the same material quantities and functional unit used in the LCA to calculate benchmark life-cycle carbon emissions for each railway superstructure. The Carbon Emission Index (CEI) was defined as the ratio of actual emissions to benchmark emissions, thereby quantifying each system's deviation from the low-carbon reference condition.

2.1 Overview of Life Cycle Assessment Based on Carbon Footprint Analysis

A thorough examination of the life cycle of superstructures was conducted from a carbon dioxide emissions viewpoint, focusing on meeting technical criteria like sustainable design and resilient infrastructure. This evaluation considers carbon emissions across all stages of the life cycle, including production, construction, operation, maintenance, and end-of-life. Through a comprehensive life cycle carbon footprint analysis of materials, a detailed assessment of carbon emissions was carried out to accurately determine emission factors for each material type. Given the study's methodology and emphasis on carbon footprint assessment, the evaluation process for different superstructure designs is presented in Figure 1.

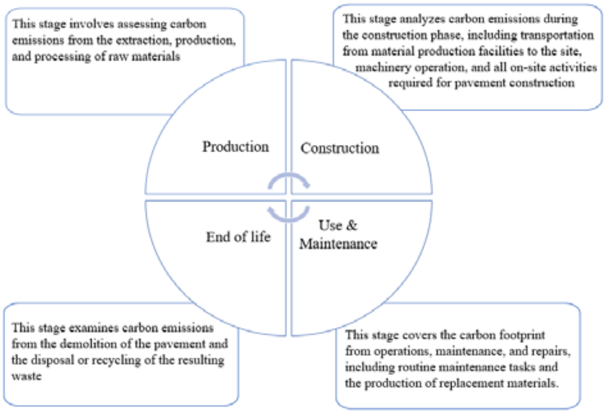


Fig 1. Carbon Footprint Analysis of Superstructures in Life Cycle Assessment

As shown in Figure 1, the life cycle assessment based on carbon footprint analysis is organized into four stages:

- Phase 1: This stage involves assessing carbon emissions from the extraction, production, and processing of raw materials.
- Phase 2: This stage covers the carbon footprint from operations, maintenance, and repairs, including routine maintenance tasks and the process of replacement materials.
- Phase 3: This stage analyzes carbon emissions during the construction phase, including transportation from material production facilities to the site, machinery operation, and all on-site activities required for superstructure construction.
- Phase 4: This stage examines carbon emissions from the demolition of the superstructure and the disposal or recycling of the resulting waste.

2.2 Assessment of Carbon Emissions from Materials in railway superstructures

To assess the carbon emissions of railway superstructure materials, the required materials for the superstructure were first identified. Then, the carbon emission factor per unit of each material was obtained from previous studies. Specifically, Seo and Kim [12] reported the emission factors for rebar, asphalt, rail pad, and bolt and fastener, Purnell [24] provided the emission factor for concrete, and Hulail et al. [25] provided the emission factor for ballast. Based on these unit emission factors, the carbon emissions were then attributed and extrapolated to the material quantities required for one kilometer of railway superstructure as listed in Table 1.

To assess carbon emissions from rail production across railway superstructures, data were obtained from life cycle assessments (LCAs) and Environmental Product Declarations (EPDs) published by major and well-established rail manufacturers. These datasets provide verified carbon emission factors expressed as kilograms of CO_2-equivalent per ton of rail produced. The reported emission factors were used to determine the carbon emissions associated with the required rail quantities for 1 km of railway track. For the assessment, a value of 2.56 kg CO_2-equivalent per ton of rail was selected. This value was determined as the median of emissions data reported by various manufacturers, providing a representative value for evaluating the environmental performance of rails. An overview of carbon dioxide emissions of rail per ton is presented in Table 2.

Table 1. Carbon Dioxide Emission Factors per Unit of Superstructure Material

Construction Material	CO_2 Emission Factor	Unit	Reference
Concrete	432	KgCO_2-eq/t	[24]
Rebar	3466	KgCO_2-eq/t	[12]
Asphalt	184	kgCO_2-eq/t	[12]
Rail pad	3.75	kgCO_2-eq/t	[12]
Ballast	20.82	kgCO_2-eq/t	[25]
Bolt and Fastener	2	kgCO_2-eq/t	[12]

Table 2. Carbon Dioxide Emissions of Rail per ton

Facility	GWP- kg CO_2-eq/t rail	Reference
Voestalpine	2780	[26]
ArcelorMittal	2560	[27]
British Steel	2450	[28]
Nippon Steel	2440	[29]

2.3 Carbon Emission Standard Criteria by the U.S. General Services Administration (GSA)

The U.S. General Services Administration (GSA) is a federal agency that oversees and supports government infrastructure, including building standards and sustainable procurement practices. Due to its significant involvement in construction and procurement, the GSA requires Environmental Product Declarations (EPDs), which use the Global Warming Potential (GWP) metric to quantify embodied carbon and support sustainable practices on its projects [30]. The Global Warming Potential (GWP) is an index defined by the Intergovernmental Panel on Climate Change (IPCC) to compare the radiative forcing effects of various greenhouse gases relative to carbon dioxide. In this framework, carbon dioxide (CO_2) serves as the reference gas, with a GWP value of 1. This metric quantifies the energy absorption and warming potential of other greenhouse gases relative to CO_2 [30]. Embodied carbon refers to the greenhouse gas emissions associated with materials' life cycle, and GWP (CO_2e) is the metric used in Environmental Product Declarations (EPDs) to quantify it. GWP encompasses all greenhouse gas emissions throughout the entire life cycle of materials, including stages such as raw material extraction, production, transportation, and installation [31].

through the collection and analysis of third-party verified Environmental Product Declarations (EPDs) for construction materials, the U.S. General Services Administration (GSA) has established Low Embodied Carbon (LEC) requirements defining Global Warming Potential (GWP) limits to assess and reduce project-related embodied carbon and promote materials with substantially lower embodied carbon. This assessment framework supports the optimized selection of construction materials to reduce environmental impacts by driving increased use of robust, third-party verified EPD data. Ultimately, these tools help GSA manage federal construction projects more sustainably by encouraging procurement of lower-carbon materials and reducing their embodied carbon footprint. However, there were certain limitations. Specifically, official GSA emission standards have not been defined for certain materials, such as bitumen and ballast. A life cycle assessment (LCA) study revealed that the carbon emission factor for producing crushed aggregates is approximately 5.84 kg CO_2 per kilogram. This value was derived using the economic allocation method in accordance with international standards like ISO 14040 [32]. Consequently, this standardized value for ballast was utilized to ensure a comprehensive and comparable assessment of carbon emissions across different superstructure types. Other materials were assessed based on the optimized CO_2 emission values provided by the GSA as presented in Table 3.

Table 3. Optimized Carbon Dioxide Emission Factors per Unit of Material (GSA Standard)

Construction Material	CO_2 Emission Factor	Unit	Reference
Concrete	382	kg CO_2-eq/m^3	[33]
Rail	1.163	kg CO_2-eq/kg	[33]
Rebar	0.85	ton CO_2-eq/kg	[33]
Asphalt	72.6	kg CO_2-eq/ton	[33]
Rail pad	2.86	kg CO_2-eq/kg	[33]
Ballast	5.84	kg CO_2-eq/kg	[32]
Bolt and Fastener	1.9	kg CO_2-eq/kg	[33]

2.4 Carbon Emission Index (CEI)

2.4.1 Carbon Emission Index Definition

To enable a standardized comparison of the environmental performance of alternative railway superstructures, the Carbon Emission Index (CEI) was introduced as a normalized benchmark-based indicator. While total carbon emissions provide a direct measure of environmental impact, their absolute values alone do not clearly indicate whether a superstructure performs efficiently relative to an established low-carbon reference. Therefore, a benchmark-based indicator is required to evaluate the environmental performance of different alternatives on a common basis. The CEI was calculated by dividing the total carbon emissions of each superstructure alternative by the corresponding benchmark value derived from the GSA Low Embodied Carbon (LEC) criteria, as shown in Equation (1). This benchmark represents a reference level of carbon emissions for the materials included in the assessment and provides a basis for evaluating the deviation of each alternative from a low-carbon design condition.

A CEI value equal to 1 indicates that the carbon emissions of a given superstructure are consistent with the benchmark value. Values greater than 1 indicate emissions exceeding the benchmark and therefore a less favorable environmental performance, whereas values lower than 1 indicate lower carbon emissions and superior environmental performance relative to the benchmark. Consequently, the CEI enables direct comparison among different railway superstructure systems and facilitates the identification of alternatives with lower carbon impacts.

$$\mathrm{CEI} = \frac{\Sigma\left[\mathrm{M} \times \mathrm{EF}_{(\mathrm{GWP})}\right]}{\Sigma\left[\mathrm{M} \times \mathrm{EF}_{(\mathrm{GSA})}\right]} \quad (1)$$

Where:

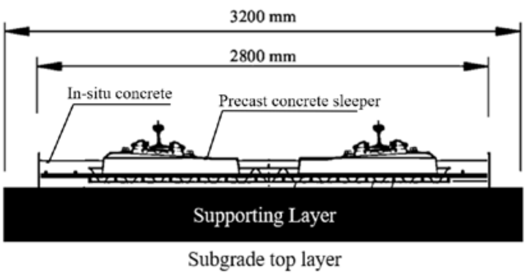
- M is material quantities per one kilometer of railway track (kg)
- $EF_{(GWP)}$ is carbon dioxide emission factor (M*GWP-kg CO_2-eq / kg material)
- $EF_{(GSA)}$ is Optimized carbon dioxide equivalent emission factor based on GSA criteria (M*GSA-kg CO_2-eq / kg material)

Several indicators have been proposed in the literature to assess environmental performance and carbon-related sustainability from different perspectives. Fakher [19] employed the Ecological Footprint Index to evaluate environmental quality, while Mohsin et al. [20] developed an Aggregated Composite Index (ACI) that combines environmental and energy indicators to rank countries according to sustainability performance. Chen et al. [21] introduced the Carbon Emissions Reduction Index (CERI) to quantify the pressure of carbon reduction policies by considering both emission volumes and their regional allocation. More recently, Mansour and Nowak [22] proposed the Carbon Footprint Reduction Index (CaFRI) for assessing and improving the sustainability of laboratory analytical methods, whereas Mosly [23] developed the Construction Carbon Sustainability Index (CCSI) to benchmark the carbon sustainability performance of construction sectors across countries.

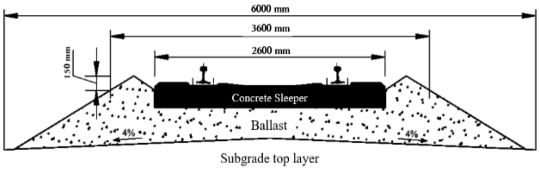
While existing indicators assess environmental performance at national, regional, industrial, or policy levels, they are not specifically designed for the comparison of railway superstructure alternatives. The Carbon Emission Index (CEI) proposed in this study addresses this limitation by relating the life-cycle carbon emissions of a railway system to a benchmark low-carbon reference. A review of the railway literature indicates that current assessments mainly rely on Life Cycle Assessment (LCA), carbon intensity measures, and emission efficiency indicators, whereas benchmark-based comparisons remain largely unexplored. Consequently, the CEI offers a straightforward and standardized framework for evaluating and comparing the relative carbon performance of alternative railway superstructure systems.

3. Railway Superstructures

the railway track is the superstructure placed on the top of the railway body [35]. The most popular kind of track is ballasted [36]. The ballasted track basically consists of a flat framework—obtained by properly linking rails, sleepers and fasteners—and a layer of crushed stone called ballast. Below the latter, if necessary, a further layer called sub-ballast is placed. On the other hand, slab tracks are commonly used on high-speed railway lines and light rail systems [35]. The so-called slab track is a concrete or asphalt surface This structure is made of stiff and brittle materials, hence the required elasticity can be obtained by inserting elastic components below the rail or/and the sleeper [37]. There are many different slab track designs, (e.g. including OBB, Rheda, ERC, Balfour Beatty, Shinkansen, PACT, ATD and etc). In this study, among the various slab track systems, Rheda 2000 was chosen as the representative system for comparison with ballasted track. Hereafter, the term “slab track” refers to Rheda 2000. The Rheda 2000 system is flexible enough to allow for design adaptations according to the individual constraints of a project. The basic system structure consists of modified twin-block sleepers, securely and reliably embedded in a monolithic concrete slab. Highly elastic rail fastenings are employed to ensure the required vertical rail deflection, which contributes to load distribution and smooth train operation. Rail fastening systems such as Vossloh 300, combined with a soft elastic pad of 10–12 mm thickness, are used [38]. The cross-sections of these railway systems are shown in Figure 2.



(a) RHEDA 2000 slab track



(b) ballasted track

Figure 2. Common Railway Superstructures; a) Ballasted Track, b) Slab Track

4. Material Inventory of Railway Superstructures

For the carbon emission assessment, representative ballasted and slab track systems were assumed, and the corresponding material quantities for a one-kilometer track section were defined for each system. The inventories included all major superstructure components that contribute to material consumption and associated carbon emissions.

For the ballasted track, the considered components consisted of the ballast layer, sub-ballast layer, concrete sleepers, UIC 60 rails, fastening systems, and rail pads. The quantities adopted in the analysis were 1,155 m^3 of ballast, 1,050 m^3 of sub-ballast, 264 m^3 of concrete used in sleepers, 120 t of UIC 60 rail, 30 t of fastening systems and bolts, and 1 t of rail pads per kilometer of track. Similarly, the slab track inventory included the concrete slab, concrete sleepers, reinforcing steel, UIC 60 rails, fastening systems, and rail pads. For a one-kilometer section, the slab track system required 550 m^3 of concrete for the track slab, 114 m^3 of concrete for sleepers, 65.208 t of reinforcing steel, 120 t of UIC 60 rail, 30 t of fastening systems and bolts, and 1 t of rail pads. These material quantities constituted the basis of the carbon emission analysis and were subsequently used to estimate the total carbon footprint of each track system.

5. Evaluation of Railway Superstructures Based On Carbon Footprint Emission

To estimate the carbon footprint of a 1-km railway superstructure, the material requirements were combined with the corresponding emission factors reported in Table 1. The resulting emissions were then summed to obtain the total CO_2 emissions per kilometer of track, which are listed in Table 4.

Table 4. CO_2 Emissions for 1 km of Railway Superstructures (ton)

Materials	Slab track	Ballasted track	Ref.
In-situ concrete	237.6	-	[25]
Sleeper concrete	49.25	114.05	[25]
Rebar	226.01	-	[12]
Rail	307.2	307.2	[27]
Fastening system	0.06	0.06	[12]
Rail Pad	3.75	3.75	[25]
Ballast	-	38.48	[25]
Sub-Ballast	-	34.98	[25]
Total CO_2 Emissions (ton)	823.87	498.51	

As shown in Figure 3, the total CO_2 emissions associated with a 1-km slab and ballasted tracks were estimated about 843 and 498 t CO_2, respectively. In the case if slab track, the total CO_2 emissions includes 114 m^3 of sleeper concrete, which emits 49.25 t CO_2, and 550 m^3 of In-situ concrete, which emits 237.6 tons. Use of 65.2 tons of Rebar emits 226 t CO_2, while 120 tons of rails emits 307.2 t CO_2. The 30 tons of fasteners emits 0.06 t CO_2, and 1,000 kg of rail pads emits 3.75 t CO_2.

For one kilometer of ballasted track, total carbon emissions amount to 498.51 tons per kilometer. Within this length, 1,155 m³ of ballast is used, emitting 38.48 tons of carbon1,050 m³ of sub-ballast contributes 34.98 tons of emissions, and 264 m³ of sleeper concrete accounts for 114.05 tons of carbon emissions. Furthermore, the use of 120 tons of rails results 307.2 tons of carbon emissions, 30 tons of fasteners produces 0.06 tons of carbon, and 1,000 kg of rail pads corresponds to 3.75 tons of carbon emission.

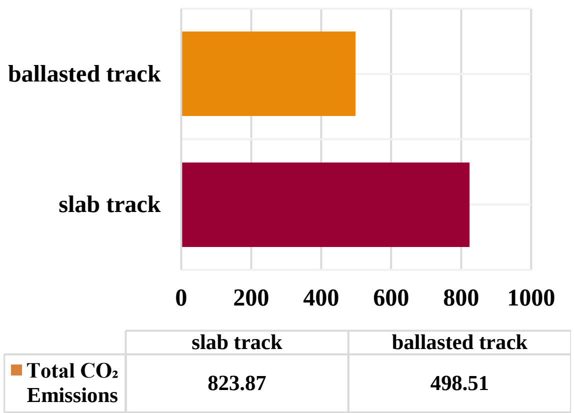


Figure 3. CO_2 Emissions of Railway Superstructures (Ballasted and Slab Tracks)

6. Evaluation of Railway Superstructures Based On the Carbon Emission Index

The Carbon Emission Index (CEI) was calculated for the two railway superstructure alternatives to evaluate their environmental performance against a common low-carbon reference as shown in Figure 4. The material quantities required for a functional unit of 1 km of track were first determined for each alternative as summarized in Table 3. These quantities were then combined with the corresponding benchmark emission factors to estimate the benchmark life-cycle carbon emissions, representing the optimized low-carbon condition for each superstructure. The same procedure was applied to the actual material inventories and emission factors of the considered systems to obtain their real life-cycle carbon emissions. Finally, the CEI was derived as the ratio of actual emissions to benchmark emissions, thereby quantifying the deviation of each alternative from the reference condition.

Table 5 summarizes the calculated Carbon Emission Index (CEI) for each of railway superstructure tapes. The results show that the ballasted track obtained a CEI of 1.55, whereas the slab track reached a higher value of 1.62, indicating a greater deviation from the benchmark. Although both systems exceeded the ideal low-carbon criterion, the ballasted track performed slightly better than the slab track in terms of relative carbon efficiency. This marginal advantage can be attributed to the lower material intensity and simpler manufacturing processes associated with ballasted track components, which collectively reduce its overall life-cycle emissions.

Table 5. Carbon Emission Index (CEI) of Railway Superstructures

Superstructure System	slab track	ballasted track
Total CO_2 Emissions (tons)	823.87	498.51
GSA Standard Criteria (tons)	508.43	320.81
Carbon Evaluation Index (CEI)	1.62	1.55

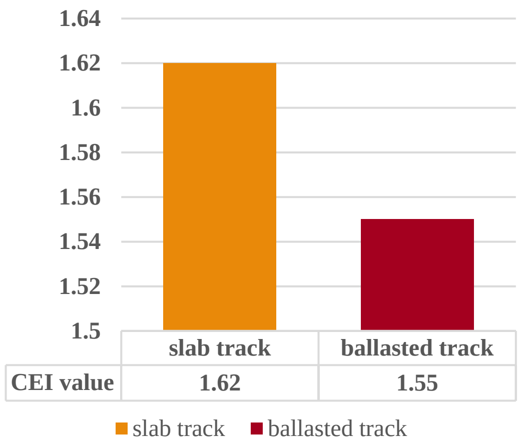


Figure 4. CEI Values of Railway Superstructures (Ballasted and Slab Tracks)

7. Conclusion

This study quantified the material requirements for one kilometer of two representative railway superstructure systems, namely a conventional ballasted track and a ballastless track represented by the RHEDA 2000 system. Based on these material inventories, life-cycle carbon dioxide emissions were calculated using material-specific emission factors under both actual and low-carbon benchmark scenarios. The environmental performance of the two systems was then assessed across the production, construction, operation, and end-of-life phases. To facilitate a standardized comparison, a benchmark-based framework was developed, enabling the evaluation of both absolute emissions and relative environmental performance.

The results showed that the ballastless track has a higher life-cycle carbon footprint than the ballasted track. Total carbon dioxide emissions were estimated at 823.87 t CO_2/km for the ballastless track and 498.51 t CO_2/km for the ballasted track, indicating a greater environmental impact for the ballastless system. This difference is primarily attributable to the greater use of in-situ concrete and reinforcing steel in the ballastless structure. In fact, rails, rebar, and in-situ concrete are the dominant emission sources in the ballastless system, whereas rails and sleeper concrete account for the largest shares in the ballasted system, with ballast and sub-ballast contributing comparatively less.

To complement the absolute emission results, the Carbon Emission Index (CEI) was introduced as a normalized indicator for evaluating each system relative to the low-carbon benchmark. The CEI values were 1.55 for the ballasted track and 1.62 for the ballastless track. These results indicate that both systems exceed the benchmark condition; however, the lower CEI value of the ballasted track suggests a comparatively lower carbon impact and a more favorable environmental performance.

Therefore, these results showed that the ballasted track benefits from a more flexible material composition and less energy-intensive manufacturing, resulting in a marginally lower carbon footprint over its entire service life.

Overall, the findings of this study confirm that the choice of track system has a significant influence on construction-stage carbon emissions and that environmental performance should be considered as an important criterion in railway infrastructure decision-making. The proposed assessment approach provides a practical basis for comparing alternative track systems and supports the selection of solutions with lower environmental impact.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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