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LCA COMPARISON OF SLAB TRACK VS. BALLASTED TRACK

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Abstract

When it comes to reducing the rail systems' ecological footprint, it is essential to assess and compare lifecycle (LC) greenhouse gas (GHG) emissions. In the presented study this is executed for the two main railway track construction types: ballasted track and slab track. Preexisting soil conditions are considered as they significantly influence maintenance demands, service life and consequently life cycle costs. This study is executed for Austrian boundary conditions with speeds up to 250 km/h. The degree of emission reduction varies according to the additional soil reinforcement treatments employed, which in turn depend on the preexisting soil conditions. The findings indicate that the use of ballasted track leads to 11-20% lower LC GHG emissions. Poor soil conditions can increase LC GHG emissions for both track designs by as much as 26%, underscoring the importance of incorporating this parameter into the railway track lifecycle assessment (LCA). Compared to slab track construction, this type results in increased concrete mass and necessitates more extensive soil enhancement measures due to the track panel's greater rigidity, despite its longer service life. In tunnel areas, GHG emissions are lower using slab track as soil reinforcements are not required owing to the pre-existing concrete base. Material production accounts for more than 80% of GHG emissions in both construction styles. Therefore, the circular economy and advancements in steel and concrete production processes have vast potential for decreasing GHG emissions.

Keywords: lifecycle assessment, railway track, ballasted track, slab track, substructure, subsoil, environmental impacts, greenhouse gas (GHG), global warming potential (GWP)

1 Introduction

Sustainable development, as defined by the United Nations [1], aims to meet current needs without risking the ability of future generations to meet their own needs. This involves balancing economic, social, and environmental factors. Rail travel is often considered a low-carbon transportation mode, accounting for just 1% of EU-28 transportation emissions in 2017 [2] despite significant passenger and freight modal splits. However, it is important to note that the carbon-intensive nature of linear transport infrastructure provision and maintenance is often overlooked. Therefore, it is vital to understand the embodied GHG emissions from constructing transportation infrastructure. At-grade construction emits 941 (±168) tCO_2eq per km, while tunnelling results in a GHG footprint 27 (±5) times greater [3]. The GHG emissions of rail infrastructure depend on the configuration used. In Austria, the railway track accounts for 55% of infrastructure related GHG emissions [4], highlighting the need to consider environmental impacts when making decisions [5].

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Ballasted track is commonly used in Austria and throughout Europe, while slab track is often preferred for high-speed railway (HSR) lines, bridges, and tunnels due to its durability and precise track geometry for HSR operations. However, substructure conditions can impact the advantages of slab track, potentially requiring extensive reinforcement in poor soil. Ballasted track is more maintainable and suitable for common applications, with settlements addressable through tamping and additional ballast [6-10].

LCA considers environmental impacts throughout the entire lifecycle. A comparison study between Spanish slab track and ballasted track [11] revealed that, despite higher environmental impacts during the production phase, ballasted track has a lower overall impact. Other studies have found that slab track has fewer environmental impacts over its service life compared to ballasted track [12-14]. However, both types of track offer potential for optimization during the use phase.

Comparisons between slab track and ballasted track often focus on the superstructure. However, subsoil conditions significantly affect both types. Ballasted track's adaptability to imperfect substructures is an advantage over slab track, which relies on ideal conditions. This study considers additional measures for slab track under various substructure and subsoil scenarios, facilitating informed decisions for lower GHG emissions throughout the lifecycle of railway lines.

2 Methods

The study outlines its methodology, scope, and objectives in Table 1. It uses LCA to analyse the GHG emissions of two types of rail track construction, with the aim of understanding the influence of ground conditions. The analysis compares different scenarios representing subsoil conditions (including tunnel scenarios) and evaluates the consequences for subsoil improvement. Detailed information on the scenarios compared is provided in Section 2.3.

Table 1 Approach used for this study.

Methodology	Scope	Goal/Scenarios	Comparison of results
LCA for comparison of ballasted track and slab track for Austrian boundary conditions. Functional unit: GHG emissions per track meter and year	Assess and compare GHG emissions for different railway track construction types considering varying pre-existing soil conditions.	Identify the influence of varying pre-existing soil conditions due to different necessary measures of substructure enhancement.	Evaluate and draw conclusions regarding the environmental impacts of different railway track construction types.

The key input parameters for LCA are masses, materials, processes, and detailed knowledge of the operational phase, such as service life and maintenance demands under the considered boundary conditions. It is often the case that detailed data for the operational phase is unavailable. However, for Austrian conditions, comprehensive evaluations from Austrian Federal Railways provide specific input parameters. Standard elements define typical situations for various railway assets, including factors such as traffic load, curvature, rail type, and sleeper type. These elements were established in collaboration with Graz University of Technology in 2005 [14, 15] and are based on statistical analysis of historic track behaviour and maintenance data. This enables substantiated input for maintenance and service life predictions. This study benefits from detailed input data, unlike previous studies that relied on average values or had limited data access, resulting in wide variations in reported service life.

2.1 Calculations

This LCA defines the functional unit as one meter of railway track. To enable comparison, emissions will be presented per meter of track per year, considering the varying service lives of ballasted track and slab. Construction and maintenance are divided into three groups:

- Materials: Assessing the environmental impact of material production.
- Transports: evaluating emissions from material logistics to and within the construction site.
- Processes: analysing the environmental impact of construction and maintenance processes.

Table 2 provides a detailed overview of the materials, processes, and transportation methods analysed.

Table 2 Considered materials, transports, and processes.

Name	Category	Included components
Rails	Materials	Rails, rail fastening, rail pads and screws
Track supporting slab	Materials	Concrete slab incl. reinforcing steel, elastic cover layer
Casting concrete	Materials	Concrete incl. reinforcing steel
Reinforced concrete supporting plate	Materials	Concrete incl. reinforcing steel
Concrete sleepers	Materials	Concrete incl. reinforcing steel and under sleeper pads
Ballast	Materials	Gravel (grain size 16/32)
Soil exchange layer	Materials	Gravel for soil exchange layer
Asphalt layer	Materials	Asphalt for interlayer
Soil improvement	Materials	Cement for cutter soil mixing
Construction work	Process	Machinery-based construction work (incl. soil improvement)
Transport of materials	Transport	Rail or street bound transports of various materials to and within the construction site
Maintenance work	Process	Machinery-based maintenance work

Material quantities, whether in volume or mass, are determined by standardized construction designs in Austria. Environmental Product Declarations (EPDs) following EN 15804 provide information on the environmental impacts of specific materials for stages A1–A3 (named product stage) and C (called end of life stage). This study calculates the construction phase (stages A4–A5; named construction process stages) and use phase (stage B; called use stage) in particular. The study models the average transport lengths and types (truck and rail) in collaboration with the Austrian Federal Railways to assess material logistics effects, including transportation and distribution on the construction site. Emissions are determined using various transport modes detailed by the Austrian Federal Environmental Agency [16], accounting for both direct and indirect CO_2 emissions. Some emission values for construction processes are sourced from the literature [17]. Construction and maintenance processes for track work machinery are calculated in the same way for railway tracks and turnouts [5] considering the working itself, transport and traction of the machine as well as the production of machinery.

2.2 System boundaries and track construction designs

The slab track consists of precast track supporting slabs carrying rails embedded in a concrete layer. Below, a reinforced concrete supporting plate rests on the soil exchange layer, which sits on the preexisting soil. The ballasted track analysed uses concrete sleepers with under sleeper pads to support the rails [18-21], which are embedded within the ballast layer on the soil exchange layer. In the tunnel scenario, the system boundary includes the superstructure, which consists of the concrete layer and ballast bed. Soil exchange and reinforcements are not required, as railway tracks in tunnel areas are installed directly on the tunnelling sole, providing a uniform and settlement-free base layer.

2.2.1 Slab track

Slab track applications use various designs, with the Slab Track Austria (STA) system being the standard in Austria [22]. The core component of the STA system is a 5.2 m x 2.4 m precast slab, elastically supported and placed on various substructures such as tunnels, bridges, or reinforced supporting plates. An elastic layer covers the underside and tapered openings of the slab, enhancing elasticity, reducing vibrations, and decoupling it from structural supports. The integrated elastic layer in this system allows for potential repairs. A minimum joint width of 40 mm accommodates deformation due to environmental factors and provides space for drainage or cable trays. The slabs are grouted and fixed to a thin base layer of self-compacting concrete, with the tapered openings serving as anchors during concrete hardening. Unlike sleeper-based systems, STA panels can incorporate openings in the track for inspection and bearing shafts as needed.

2.2.2 Ballasted track

The railway track consists of multiple components that work together to maintain stability and functionality. Sleepers support the rails and distribute the weight of the vehicles evenly, ensuring gauge maintenance and lateral stability. The ballast layer serves as the foundation of the track, dispersing traffic loads and enhancing durability. Proper drainage, facilitated by the ballast layer, prevents water accumulation, safeguarding against track instability and degradation. Drainage systems, such as ditches or culverts, are commonly used to manage water runoff. It is important to ensure that these systems are integrated effectively to prevent flooding and other water-related issues.

2.3 Boundary conditions and compared scenarios

Table 3 compares four scenarios for both slab track and ballasted track construction designs, including three soil conditions (best, medium, and poor: causing different subsoil treatments within investment) and a tunnel scenario. he different parameters of the four scenarios were used to calculate the GHG emissions. Different soil conditions each require an adapted substructure design. The service lives of the respective layers also change. The suitability of soil conditions greatly impacts the construction and longevity of railway tracks. Soil is classified as best if it requires no enhancements to support the track, medium if minor improvements suffice, and bad if extensive measures like cutter soil mixing are needed. Slab tracks, with a 60-year service life, and ballasted tracks, lasting 43 years, have different requirements. Slab tracks may need asphalt layers for ballast separation, whereas ballasted tracks may reuse 50% of the ballast during renewal. For slab tracks over bad soil, soil improvement measures are necessary, typically involving a 55 cm thick layer applied via cutter soil mixing. The choice between these measures depends on factors like expected service life and soil conditions.

Table 3 Overview of compared scenarios.

Parameter	best soil conditions		medium soil conditions		bad soil conditions		tunnel track	
	slab track	ball. track	slab track	ball. track	slab track	ball. track	slab track	ball. track
service life track [years]	60	43	60	43	60	43	60	43
use of asphalt layer	no	yes	yes	yes	yes	yes	no	no
factor service life asphalt	-	2	2	2	1	1	-	-
soil exchange [m]	0.5	0.5	1	0.5	1	0.7	0	0
factor service life soil ex.	1	2	1	2	1	1	-	-
reinforced concrete supporting plate [m]	0.3	0	0.3	0	0.3	0	0	0
share of reused ballast	-	0.5	-	0.5	-	0.5	-	0.5
share of cutter soil mixing	0	-	0	-	1	-	0	-

3 Results

Figure 1 shows the results of the four scenarios described earlier, calculated per meter of track length and year of service life. The data indicates that the slab track produces significantly higher absolute GHG emissions compared to the ballasted track. When adjusted based on the service life of each track type (60 years for slab track and 43 years for ballasted track, as per Table 3), comparable data for various substructure conditions emerge.

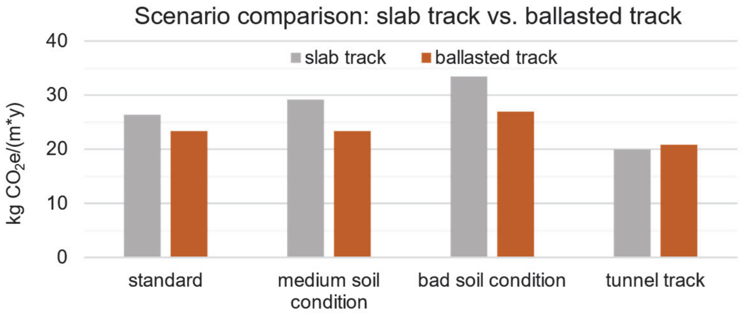

Figure 1 Comparison of GWP results for each scenario (per year and meter).

The data indicates that in all open track scenarios, GWP emissions per meter and year of slab track exceed emissions of ballasted track. Conversely, tunnel areas show the opposite result. The analysis shows those materials that have the highest GWP impact, particularly rails with their fastenings, which account for approximately half of the overall impact for both types of railway track construction (in total 650 kg CO_2e/m). However, when comparing processed masses (250 kg/m), rails only make up about 1.5% for slab track and less than 3% for ballast track. This difference highlights a common trend in transportation infrastructure, where high-quantity components like ballast and soil tend to have lower CO_2 intensity.

Material flow analysis could be valuable in developing holistic sustainability strategies, including circular economy approaches. Plastics, including under sleeper pads, exhibit similar patterns to other materials. Conversely, components such as ballast, gravel, and soil exchange layers have high mass but relatively low GWP impact. In the scenario where the soil conditions are optimal, slab track necessitates approximately 18,044 kg per meter of track length, whereas ballasted track requires 8,315 kg/m of total mass.

4 Discussion & conclusions

The data indicate that slab track has higher GHG emissions for open track configurations, with the difference becoming more pronounced in poorer subgrade conditions. This is due to the rigid superstructure of slab track, which has a longer lifespan but presents maintenance challenges, especially when dealing with uneven settlements. Therefore, it is essential to achieve a settlement-free substructure for the implementation of slab track. This requires more extensive soil reinforcement measures, particularly in scenarios with medium or poor preexisting soil conditions. Within tunnel areas, there is a reduced need for soil reinforcements due to the already settlement-free tunnel sole. This has a more positive effect on slab track than on ballasted track, as slab track has higher demands on its supporting layers and requires less to no maintenance in case of settlements. In summary, this study compares slab and ballasted track considering various preexisting soil conditions using lifecycle assessments. Key findings include:

- Ballasted track emits 11–20% less CO_2 than slab track across all scenarios for open track.
- Poor preexisting soil conditions increase CO_2 emissions by 26%, highlighting the importance of considering soil quality in lifecycle assessments.
- Slab track needs a critical service life of 73 years to balance emissions with ballasted track across all scenarios.
- In tunnel areas with existing concrete soles, slab track application reduces CO_2 emissions by 4%.
- Material production accounts for over 80% of GHG emissions for both construction types. This shows that there is great potential for avoiding CO_2 emissions, especially in steel and concrete production.

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