sustainability

MDPI

Article

In-Depth Lifecycle Assessment of Ballasted Railway Track and Slab Track Considering Varying Subsoil Conditions

Dieter Knabl [1,*] and Matthias Landgraf [2]

[1] Institute of Railway Engineering and Transport Economy, Graz University of Technology, 8010 Graz, Austria
[2] Evias Rail Consulting, 8047 Graz, Austria; matthias.landgraf@evias.at
* Correspondence: dieter.knabl@tugraz.at; Tel.: +43-316-873 (ext. 6219)

Abstract: This study assesses and compares lifecycle (LC) greenhouse gas (GHG) emissions from the two main railway track construction types: ballasted track and slab track. In this study, preexisting soil conditions are considered, as they significantly influence necessary measures during the construction phase for each type. This study is executed for Austrian boundary conditions with speeds up to 250 km/h. The results show that ballasted track is associated with 11–20% lower LC GHG emissions, whereby the variation in relative emission reduction is associated with additional soil reinforcement treatments due to varying preexisting soil conditions. Poor preexisting soil conditions increase LC GHG emissions by 26%, underlying the necessity to integrate this parameter into the lifecycle assessment of railway track. In contrast to the higher service life of slab track construction, this type amounts to higher masses of concrete and demands more extensive measures for soil enhancement due to the higher stiffness of the track panel. Only in tunnel areas does slab track cause lower GHG emissions since soil reinforcements are not necessary due to an existing concrete base layer after tunnel construction. For both construction types, over 80% of the GHG emissions stem from material production. Hence, circular economy as well as innovations within steel and concrete production processes hold significant potential for reducing GHG emissions.

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

check for updates

Citation: Knabl, D.; Landgraf, M. In-Depth Lifecycle Assessment of Ballasted Railway Track and Slab Track Considering Varying Subsoil Conditions. *Sustainability* **2023**, *15*, 12974. https://doi.org/10.3390/su151712974

Academic Editor: Giovanni Leonardi

Received: 21 July 2023
Revised: 24 August 2023
Accepted: 26 August 2023
Published: 28 August 2023

1. Introduction

The United Nations World Commission on Environment and Development [1] describe sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability should therefore strive for a balance between economic vitality, social equality, and environmental health.

Rail travel is already a low-carbon means of transportation. Only 1% of all transportation-related greenhouse gas emissions in the EU-28 in 2017 came from rail travel [2], despite the fact that the modal split for rail transportation is 8% and 18% for passenger and freight transport, respectively.

These figures include railway operation only, i.e., direct and indirect emissions from burnt fuel and electricity consumption. Most statistical figures of GHG emissions in transportation neglect provision and maintenance of infrastructure. Due to the need for building, maintaining, and replacing transportation-related infrastructure assets, linear transport infrastructure is carbon-intensive.

An increasing amount of the literature emphasizes the significance of comprehending the embodied GHG emissions from the construction of transportation infrastructure. The overall lifecycle emissions from transportation modes are understated if just tailpipe emissions are considered, according to research conducted in the United States in 2007 [3,4]. Olugbenga et al. [5] reviewed 100 publications and produced the most thorough analysis of embodied emissions in rail infrastructure. In this study, the amount of depth of the LCA calculation, the use of real-world data, and the consideration of embodied effects were all taken into account. The resulting embodied emissions range from 0.5 to 12,700 tCO_2eq per km; a large percentage of this difference is determined by how much of the railway line is at-grade, elevated, or in a tunnel. According to the statistical modelling results, at-grade rail construction results in an overall embodied carbon dioxide (GHG) footprint of 941 (±168) tCO_2eq per kilometer, whereas tunnelling results in a GHG footprint that is 27 (±5) times greater. Specifically addressing Austrian conditions, Landgraf et al. [6] calculated embodied greenhouse gas emissions by comparing railway infrastructure assets (track, tunnel, geotechnics, structures, power supply, noise barriers, communications, signaling) and their contributions to the overall carbon footprint of railway infrastructure. The findings show that railway track is responsible for 55% of GHG, leading to an in-depth analysis of this asset. Moreover, turnouts were examined in detail, and the authors also suggested using an evaluation method to calculate the environmental costs of railway infrastructure [7]. This provides support for including environmental impacts in the strategic decision making and procurement process.

The standard track in Austria is constructed using ballasted track, with slab track (ballastless track) used in areas with long tunnels. In Europe, ballasted track makes up an overwhelming part of the European rail network, i.e., 216,000 km in 2019 [8]. By 2012, 9256 km of slab track had been installed within the European rail network [9]. This number is constantly growing, as slab track is the predominant option used when constructing highspeed railway (HSR) lines or long bridges and tunnels. This is mainly because slab track guarantees the long-lasting, accurate track geometry required for HSR operations. Solid concrete slab provides stability, being able to withstand heavy loads and wear from train traffic over time without significant deformation or settlement. This results in longer track life, reducing the need for frequent replacement and the associated costs. This type of track also is associated with low demand for maintenance, which can significantly reduce operating costs and downtime. However, these advantages depend strongly on the substructure and its load bearing capacity. In contrast to tamping and ballast cleaning of ballasted track, the track geometry of slab track sections cannot be restored if settlements in the substructure occur. Thus, in case of poor preexisting soil conditions, reinforcement measures are more extensive for slab track construction than ballasted track. Railway track in long tunnel and bridge sections is already installed on civil engineering structures, which is why this is the ideal field of application for slab track [10–14].

The main advantage of ballasted track is its maintainability, which is why it is used for all common applications, such as mixed traffic that attains moderate vehicle speeds. In case of settlements, tamping measures and additional ballast enable the restoration of track quality. In addition, at the end of service life, superstructure, ballast, and substructure can be renewed using track-bound construction machinery at low economic and time costs. The latter is also of utmost importance, as less downtime for maintenance and renewals leads to greater availability and punctuality. In Austria, ballasted track is standard except for long bridges and tunnels. This study should support the decision making process on whether ballasted or slab track may be installed on future lines with maximum speeds of 250 km/h.

Lifecycle assessment (LCA) according to EN 15804 [15] considers the environmental impacts throughout the whole lifecycle. A study on the environmental impacts caused by slab track in Spain [16] compared ballasted track to slab track using the Rheda 2000 system, which has an underlying service life of 60 years compared to ballasted track, which has a service life of 25 years; in the case of ballasted track, this is a highly conservative assumption. This work states that the largest part of the impact occurs in the production phase (64%), mainly due to the production of concrete and steel for the slab track superstructure. In total, the study found that the environmental impact of ballasted track, nevertheless, is lower than that of slab track. However, preexisting soil conditions were assumed to be adequate; thus, a standardized base layer for each type was considered.

A study from the UK [17] concluded that slab track shows a lower number of environmental impacts over its service life for HSR applications because the emissions due to concrete and steel production are balanced out by the longer service life of slab track applications. These calculations are based on service lives of 60 years (slab track) and only 20 years (ballasted track).

Based on data for the Austrian Brenner Base Tunnel, Hausberger et al. [18] compared different ballastless track types with a slab track inside and outside a tunnel area. The underlying service lives were 30–40 years for ballasted track and 80–100 years for slab track. The focus was set on comparing superstructure type, whereas the substructure was assumed to be in good condition for every scenario, highlighting that varying substructure conditions could not be considered. The study concluded that the main optimization potential for both construction types lies within the use phase. This differs from the majority of the literature, which can be explained due to the fact that this study was calculated over a lifetime of 80 and 200 years, respectively. Hence, renewal measures (i.e., reinvestments) were integrated into the use phase.

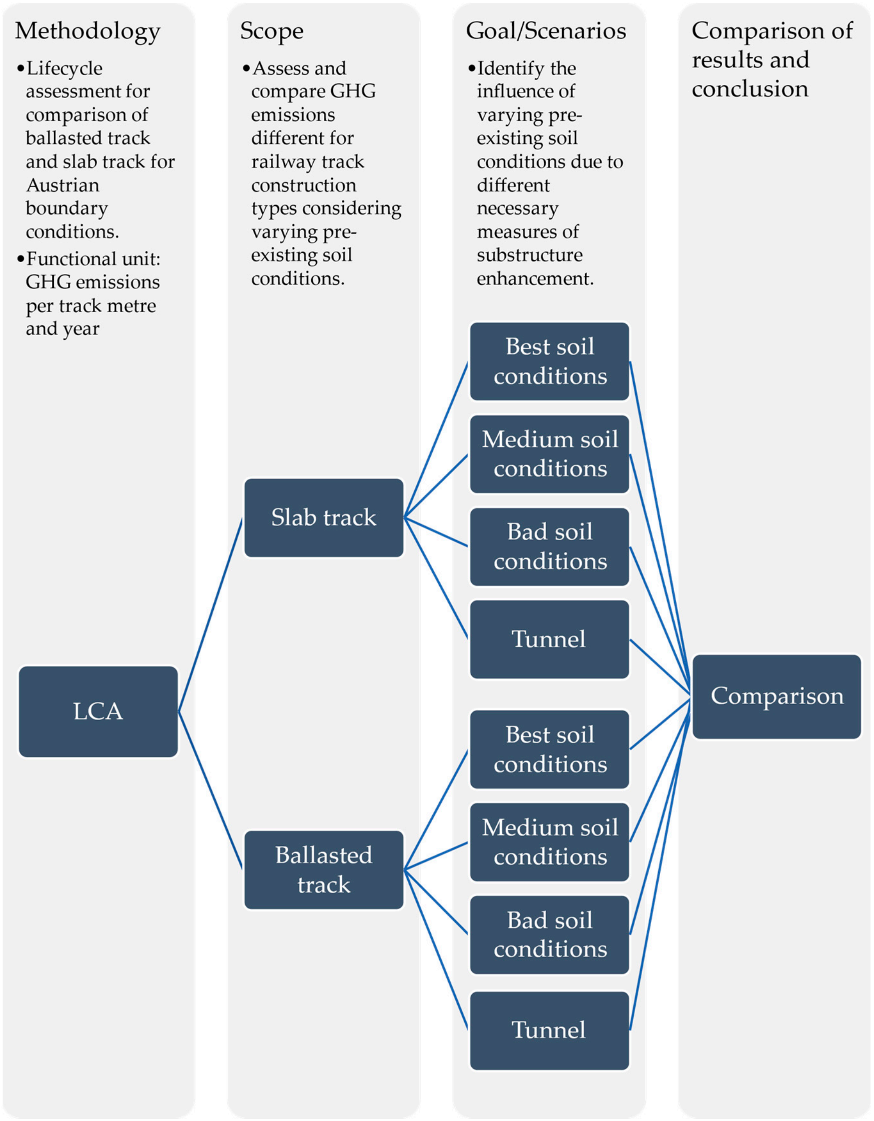
A German study by Hansen et al. [19] compared the conventional ballasted track with the Rheda Classic slab track with monoblock sleepers on a component level. This includes sleepers and ballast for ballasted track and the concrete block for Rheda Classic. Their study concluded that the analyzed components of slab track shows a much higher environmental impact.

With regard to lifecycle costs within Austrian boundary conditions, Marschnig [20] compared superstructure elements only for lines with a maximum speed of 250 km/h. A comparison between ballasted track with concrete sleepers and under sleeper pads (USP) with slab track shows that the lifecycle costs, including depreciation and maintenance costs, are similar. Slab track shows a higher portion of costs for depreciation, since investment costs are higher. Ballasted track shows a higher portion of costs for maintenance. The underlying data for service life and maintenance demands for both ballasted and slab track are based on in-depth evaluations by Austrian Federal Railways, which are also used for the present study.

In conclusion, previous comparisons between slab track and ballasted track have mainly focused on the superstructure. In cases where substructure was included, subsoil was considered adequate and a standardized base layer for each construction type was regarded. However, many studies have elaborated that varying subsoil conditions have significant and different effects for slab track and ballasted track. One of the main advantages of ballasted track is the possibility to restore track quality by executing tamping measures. If settlements are already too high, short sections can be improved using ballast cleaning and sleeper exchange with short associated downtimes and costs compared to structural improvements made when using slab track. This means that slab track depends much more on perfect substructure conditions with low to no soil settlement. In this paper, we consider the additional measures for slab track with regard to varying substructure and subsoil by taking a scenario-based approach. This allows for conducting evaluations and comparisons based on various underlying subsoil qualities. Since preexisting soil conditions are often heterogeneous, this study is a crucial improvement in the design phase of railway lines and sections. Based on in situ conditions, practitioners can decide which construction type shows lower GHG emissions within the lifecycle.

2. Methods

The methodology, scope, and goal of this study are visualized in Scheme 1. The methodology of LCA is applied on two types of railway track construction to identify the influence of subsoil conditions by comparing the GHG emissions of different scenarios regarding soil conditions (and tunnel) and its consequences with regard to soil improvement. See Section 2.3 for details concerning the compared scenarios.



Scheme 1. Approach used for this study.

The main input parameters for an LCA are masses, materials, processes, and in-depth knowledge over the use phase (service life and maintenance demands under specific boundary conditions). Detailed data of the use phase often remains unknown or is considered by using overall average values. For Austrian boundary conditions, we can use detailed evaluations from Austrian Federal Railways describing all relevant input parameters for the operational phase for specific existing boundary conditions.

The so-called standard elements describe a typical situation for the considered asset; for example, a standard track kilometer defines a specific set of boundary conditions within the network. Boundary conditions are defined by traffic load, curvature, line speed, rail type (profile and steel grade), sleeper type, type of superstructure (slab track or ballasted), as well as ballast and substructure conditions. Each set of these parameters results in different expectations for service life and maintenance demands over the lifecycle of railway track. These standard elements have been developed for various assets, such as a track, switch, bridge, railway crossing, platform, signaling technology, overhead line, stops, interlockings, safety technology at railway crossings, and many others. These standard elements have been established networkwide by Austrian Federal Railways in close cooperation with Graz University of Technology since 2005 [6,21]. They are based on statistical analysis of historic behavior of railway track with certain boundary conditions, analyzing actually achieved service lives as well as maintenance documentations dating back to 2002. Moreover, maintenance and renewal predictions stemming from track geometry data analytics as well as experience from regional engineers and expert groups were obtained to specify expected service lives and maintenance demands for varying boundary conditions.

This allows us to use substantiated input data for maintenance demands and service life within this study. As already highlighted, there is a wide range regarding service life in previous studies with service life of ballasted track between 20 and 40 years and slab track between 60 and 100 years. This is due to different investment and maintenance regimes in different countries or if researchers do not have access to substantiated data and must settle for average values instead.

2.1. Calculations

The functional unit for this LCA is set on one meter of railway track. Since ballasted track and slab have different service lives, results will be displayed in emissions of one meter track per year for comparison. Both the construction and the maintenance are considered divided into three categories:

- Materials: environmental impact of the material's production phase;
- Transports: emissions coming from material logistics on and off the construction site;
- Processes: environmental impact of construction and maintenance processes.

Table 1 provides an overview of all considered materials, processes, and transports including the related sources of the emission factors.

Table 1. Considered materials, transports, and processes incl. sources.

Name	Category	Included Components	Sources for Emission Factors
Rails	Materials	Rails, rail fastening, rail pads, and screws	[22,23]
Track supporting slab	Materials	Concrete slab incl. reinforcing steel, elastic cover layer	[24,25]
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	[23–25]
Ballast	Materials	Gravel (grain size 16/32)	[23]
Soil exchange layer	Materials	Gravel for soil exchange layer	
Asphalt layer	Materials	Asphalt for interlayer	
Soil improvement	Materials	Cement for cutter soil mixing	[23,26]
Construction work	Process	Machinery-based construction work (incl. soil improvement)	Author's own elaboration according Equation (1), [27]
Transport of materials	Transport	Rail or street bound transports of various materials to and within the construction site	[28]
Maintenance work	Process	Machinery-based maintenance work	Author's own elaboration according to Equation (1)

The required material quantities—either as volume or mass—are determined based on standardized construction designs in Austria. So-called environmental product declarations (EPDs) according to EN 15804 provide information about the environmental effects of specific materials for stage A1–A3 and C. Construction phase (stage A4–A5) and use phase (stage B) are specifically calculated within this study.

The average transport lengths and types (truck and rail) are modelled in accordance with Austrian Federal Railways to determine the effects of the material logistics, such as transport to the construction site and distribution on the site. Emissions are determined by referring to different types of transport modes published by the Austrian Federal Environmental Agency [28]. Direct as well as indirect CO_2 emissions are considered.

Some values for calculating emissions of various construction processes are taken from the literature [27]. Construction and maintenance processes with track work machinery are calculated for railway track in the same way as for railway turnouts [7]. The calculation for any machinery contained by the track construction process is carried out by using Equation (1):

$$\begin{aligned}
&GHG_a = W_{CO_2e} + Trac_{CO_2e} + Trans_{CO_2e} + P_{CO_2e} \\
&GHG_a = fc_{av} * (E_d + E_{ind}) * \left[\frac{1}{v_w} + n_{wu,km} * t_{wu}\right] + t_{loco} * fc_{loco,work} * (E_d + E_{ind}) * \frac{1}{v_w} \\
&+l_t * (f_{ret} + 1) * f_{mult} * \left[\frac{1}{v_{loco}} * rel_d * fc_{loco,trans} * (E_d + E_{ind}) + rel_{el} * E_{loco,el}\right] * \frac{1}{l_{c,av}} \\
&+E_{prod} * \left[\frac{1}{l_{y,av} * sl} + \frac{n_{wu,km}}{n_{wu,y} * sl}\right],
\end{aligned} \tag{1}$$

where GHG_a describe the track construction process a with W_{CO_2e} emissions of track work process itself (emissions via fuel consumption of machine operation), $Trac_{CO_2e}$ is external traction within the construction site, $Trans_{CO_2e}$ is the machine transport to and from the construction site, and P_{CO_2e} is the emission within production process of track work machinery itself. Values are usually related to one kilometer of track construction (kg CO_2e/km) and transferred into emissions per meter for the purpose of this study. In detail, fc_{av} denotes the average fuel consumption of machinery (liters per hour), E_d and E_{ind} are the direct and indirect emissions stemming from fuel consumption of the internal combustion engine (kg CO_2e per liter), v_w describes the average working speed (km/h), $n_{wu,km}$ is the number of discontinuous working units per kilometer track length (1/km), and t_{wu} is the duration of an average work unit. t_{loco} denotes the duration of traction by external loco during construction work with its average fuel consumption $fc_{loco,work}$ (liters per hour). Machinery transport emissions include distances to the construction site l_t (in km) and return distance f_{ret}. Since machinery transport is managed efficiently, the transport of multiple machines at once is considered with f_{mult} with speeds of v_{loco} (km/h), the share of diesel transport and, respectively, electric locomotive transport is denoted by rel_d and rel_{el}. Loco's average fuel consumption of the diesel locomotive is covered via $fc_{loco,trans}$ (in liters per hour), the emissions due to electric locomotive transport are denoted by $E_{loco,el}$ (kg CO_2e per km of transport). Construction length is described as and $l_{c,av}$. Since there is no specific information on emissions for machine production, we allocated EPDs of three different machines to model the emissions during the production phase E_{prod}: a multiple unit, an electric locomotive, and a milling machine. Furthermore, $l_{y,av}$ indicates the average yearly working length of the machine (km per year), sl describes the expected service life (years), and $n_{wu,y}$ is the working units carried out per year (1/year).

2.2. Track Designs and System Boundaries

Figure 1 shows both the slab track design on the lefthand side and the ballasted track design on the righthand side for open track conditions. Different layers within the sub- and superstructure are shown: The slab track consists of the precast track supporting slabs carrying the rails, which are cast in the concrete layer. Below, the reinforced concrete supporting plate for load distribution is shown as resting on the soil exchange layer, which is situated on the preexisting soil. In the case of the ballasted track, concrete sleepers with under sleeper pads (orange layer in the figures) support the rails [29–32]. The sleepers are embedded within the ballast layer, which is located on the soil exchange layer.

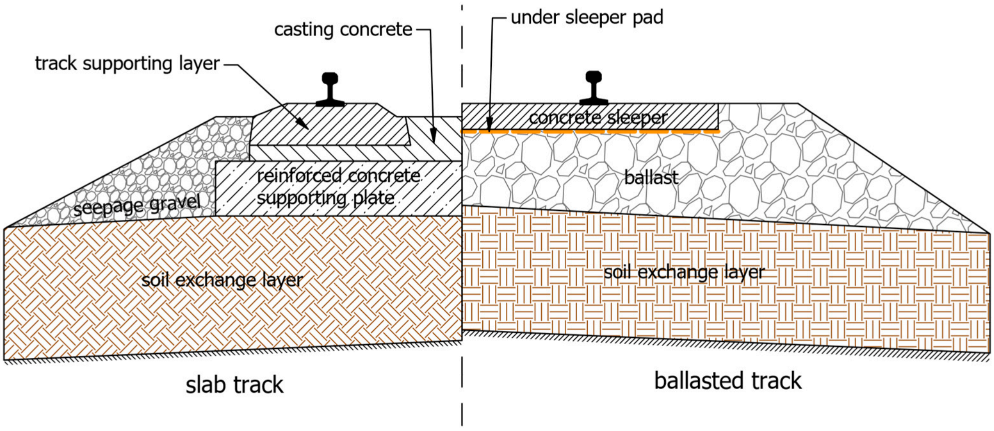


Figure 1. Sketches of the track designs compared for open track. The lefthand side represents the slab track, and the righthand side represents the ballasted track; both are shown as resting on a proper subsoil layer.

For the tunnel scenario (Figure 2), superstructure (concrete layer and ballast bed, respectively) is chosen as system boundary. Soil exchange and reinforcements are not necessary, as railway track in tunnel areas is installed on the tunnelling sole, which already delivers a homogenous and settlement-free base layer.

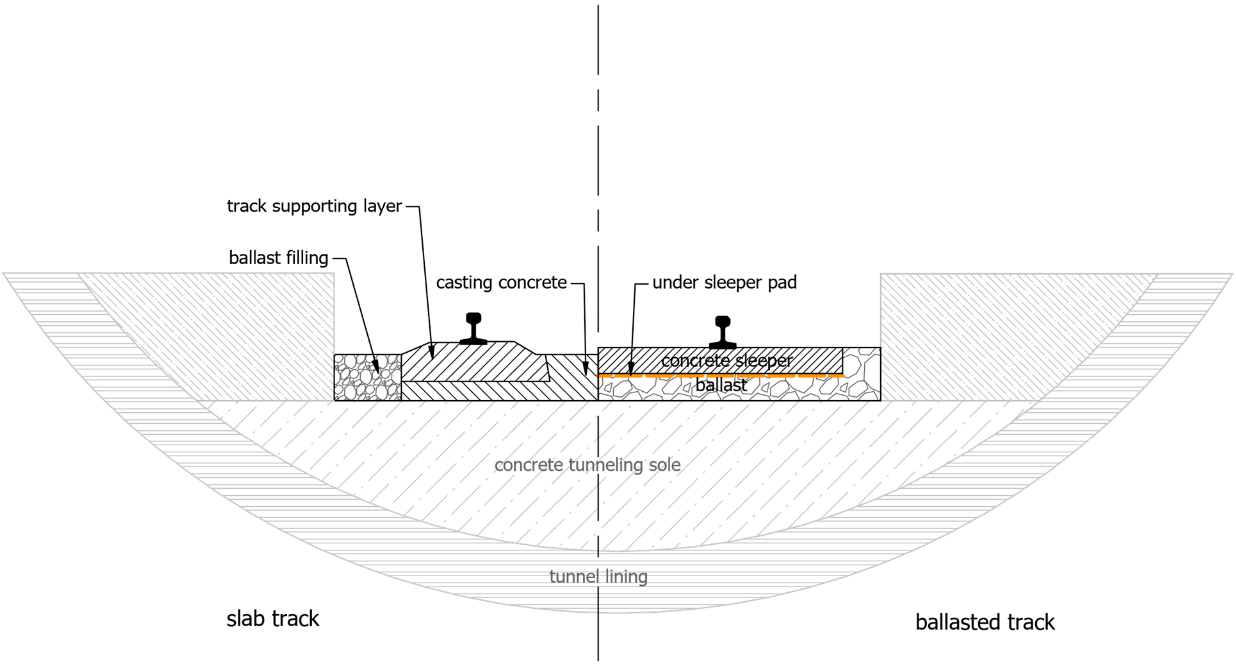


Figure 2. Sketches of the track designs compared for machine-drilled tunnels. The lefthand side represents the slab track, and the righthand side represents the ballasted track.

2.2.1. Slab Track

Different designs are used for slab track applications. In Austria, the Slab Track Austria (STA) system with precast track supporting slabs is the standard. The key element of the STA system [33] is an elastically supported 5.2 m × 2.4 m precast slab, which is placed on a solid or low-slump substructure such as a tunnel, bridge, hydraulically bonded subgrade, reinforced supporting plate, or (heavy) mass spring system. The underside of the unstressed reinforced precast slab, as well as the tapered openings, are covered with an elastic layer, which improves the elasticity of the system, reduces vibrations or structure-borne noise, and decouples it from its structural supports. The integrated elastic layer allows for repair, should this become necessary. A minimum joint width of 40 mm separates two panels to compensate for the deformation caused by environmental influences, such as creep, shrinkage, and temperature-based movement. The joint also provides space for drainage or cable trays. The slabs are grouted and fixed to a thin base layer of self-compacting concrete. As the concrete hardens, the tapered openings act as anchors, holding the panel in place both vertically and horizontally. Unlike sleeper-based slab track systems, STA panels can have openings in the track wherever these are required, for example, for inspection and bearing shafts.

2.2.2. Ballasted Track

Ballasted railway tracks are a commonly used type of track structure in the construction of railways. They consist of several components that work together to provide stability and support and ensure the proper functioning of the railway system.

The sleepers support the rails and evenly distribute the weight of the vehicles. They also maintain the gauge (the distance between the rails) and provide the track with lateral stability. The ballast layer forms the track foundation. It is placed directly on the subgrade (the underlying soil or rock formation) and serves several purposes. The ballast distributes the induced traffic loads over a wider area, providing stability and durability.

Effective drainage is crucial to prevent water accumulation, which can lead to track instability and deterioration. The ballast layer allows water to drain away, preventing the subgrade from becoming saturated. In addition, drainage systems such as ditches or culverts are often incorporated to manage water runoff.

2.3. Compared Scenarios and Boundary Conditions

Both types of track construction designs, slab track and ballasted track, are compared in four scenarios (Table 2): three different soil conditions (best (standard), medium, and bad) as well as a tunnel scenario.

Table 2. Overview of compared scenarios.

Parameter	Best Soil Conditions		Medium Soil Conditions		Bad Soil Conditions		Tunnel Track	
	Slab Track	**Ballasted Track**	**Slab Track**	**Ballasted Track**	**Slab Track**	**Ballasted Track**	**Slab Track**	**Ballasted Track**
Service life of 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	-

The variation in soil conditions reflects the suitability of the soil to support a railway track and its induced traffic loads. Thus, a preexisting soil is classified as best if no soil enhancement is necessary in order to support a newly built railway track. If little improvements such as a thicker soil replacement layer or an additional asphalt base layer in the case of slab track are sufficient, the soil is of medium quality. Bad soil condition requires extensive measures such as cutter soil mixing for the long-lasting paving of a slab track.

The need for these measures results from the lack of or heterogenous stiffness of the preexisting soil, which is necessary for the correct functioning of the slab track. Studies [34] show that the subgrade can soften depending on the composition and water content as well as standing surface water on the ground depending on the cyclic loading. The impact of these characteristics is less crucial in case of ballasted track, which is itself elastic, and track geometry can be restored by applying maintenance measures. Therefore, depending on the soil condition, it may be necessary to carry out soil improvement measures to guarantee a sufficient load bearing capacity throughout the entire service life.

Slab track has an expected service life of 60 years according to the manufacturer of this track system [33], and ballasted track has a service life of 43 years based on input data of the aforementioned standard elements approach. According to designs of Austrian Federal Railways [35,36], asphalt layers underneath the ballast bed are installed to guarantee a long-lasting dewatering surface and mitigate the mixture of ballast and soil layers for ballasted track. As for slab track, an asphalt layer is not necessary for ideal preexisting soil conditions. There is no need for this layer in tunnel areas, as the tunnel sole already provides a homogenous and long-lasting base layer. The service life for the asphalt layer depends on the soil conditions underneath; for bad subsoil conditions, there is the need to renew this layer after the service life of the superstructure. This is defined by using a factor based on the track service life; for example, a factor of 2 translates to a service life of 120 years for slab track. A certain layer thickness for the different scenarios and an associated service life factor prescribed the required soil exchange. The use of a reinforced concrete supporting plate with a standardized thickness of 30 cm is mandatory for the slab track outside of tunnels. Regarding ballasted track, 50% of the ballast can usually be directly reused [37] when track renewal becomes necessary. When bad soil conditions exist beneath slab track, soil improvement is necessary. The calculation for the comparison is based on a 55 cm thick layer applied by using cutter soil mixing along the full track length (share of 1) and width.

3. Results

The results of the four scenarios considered and described above are shown in Figure 3. The values were calculated for 1 m of track length. These results show that the absolute GWP emitted from the slab track is much higher than that from the ballasted track. Relating the absolute values to service life based on the track type yields comparable data for different substructure conditions. Service lives of 60 years for slab track and 43 years for ballasted track (see Table 1) were considered.

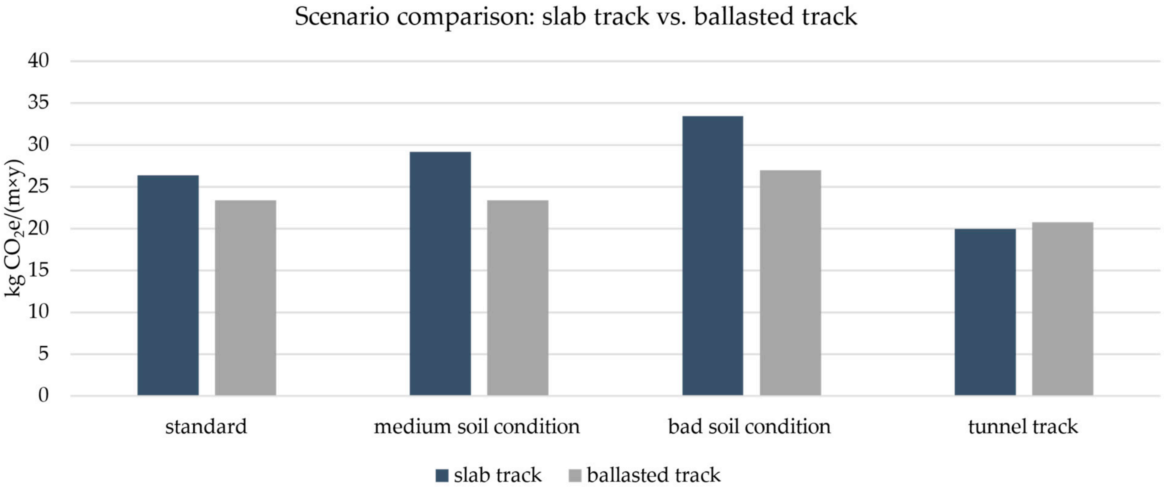


Figure 3. Comparison of GWP results for each scenario (per year and meter).

The results show that GWP emissions per meter and year of slab track are higher than emissions of ballasted track in all open track scenarios. The reverse result can be seen for tunnel areas.

The following graphs (Figures 4 and 5) show the masses in comparison to the GWP of specific components within the construction and production phase. This distribution is performed by allocating the required mass of a specific track component to the specific GWP emissions for that component.

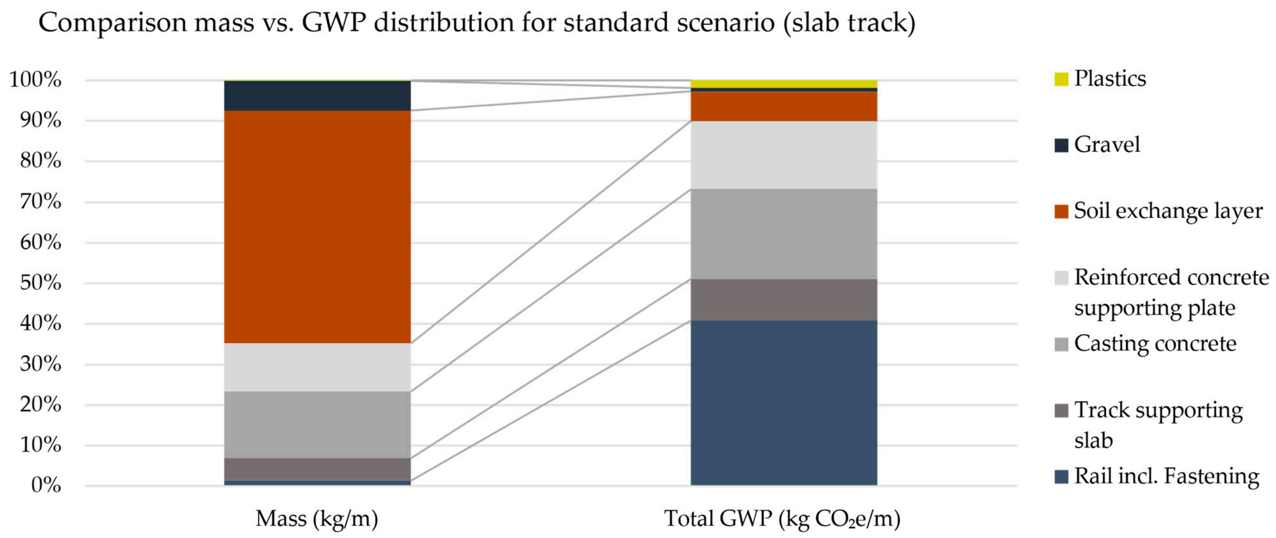


Figure 4. Comparison between the mass and total GWP distribution under the best soil conditions (standard scenario) for slab track.

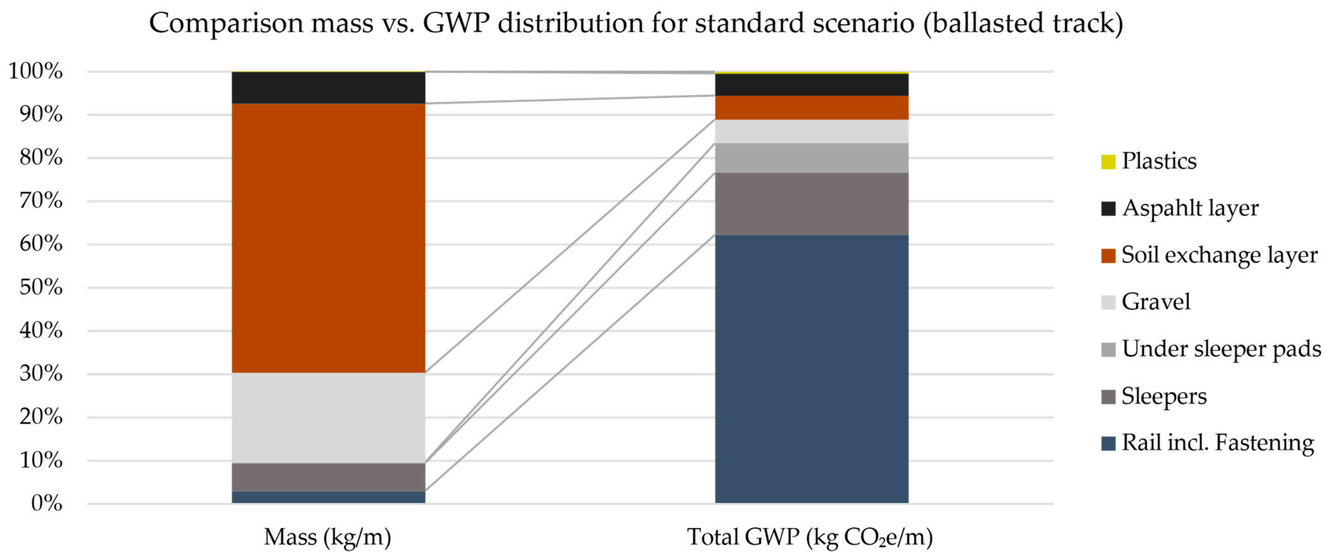


Figure 5. Comparison between the mass and total GWP distribution under the best soil conditions (standard scenario) for ballasted track.

On the one hand, this allows for identifying the components with a higher GWP impact: In particular, rails with associated fastenings are associated with roughly half the impact of railway track for both construction types (40% for slab track, 60% for ballast track). On the other hand, this analysis allows for comparing the processed masses within construction of railway track where rails only amount to about 1.5% (slab track) and less than 3% (ballast track). This contrast is often apparent for transportation infrastructure, as components of high quantity (ballast, soil) are often less CO_2-intensive, which is why material flow analysis shows great potential for a holistic sustainability strategy including circular economy. The same behavior is observed for plastics, including the under sleeper pads. The opposite is true for components such as ballast, gravel, or the soil exchange layer: these have high mass but low GWP impact.

The total mass required for slab track is approximately 18,044 kg per meter of track length in contrast to 8315 kg/m of ballasted track. This calculation is based on the "best soil conditions" scenario.

Figure 6 shows the different impacts from the categories of materials, processes, transport, and end of life. This figure shows that the production of materials has the biggest proportion of annual GWP impact.

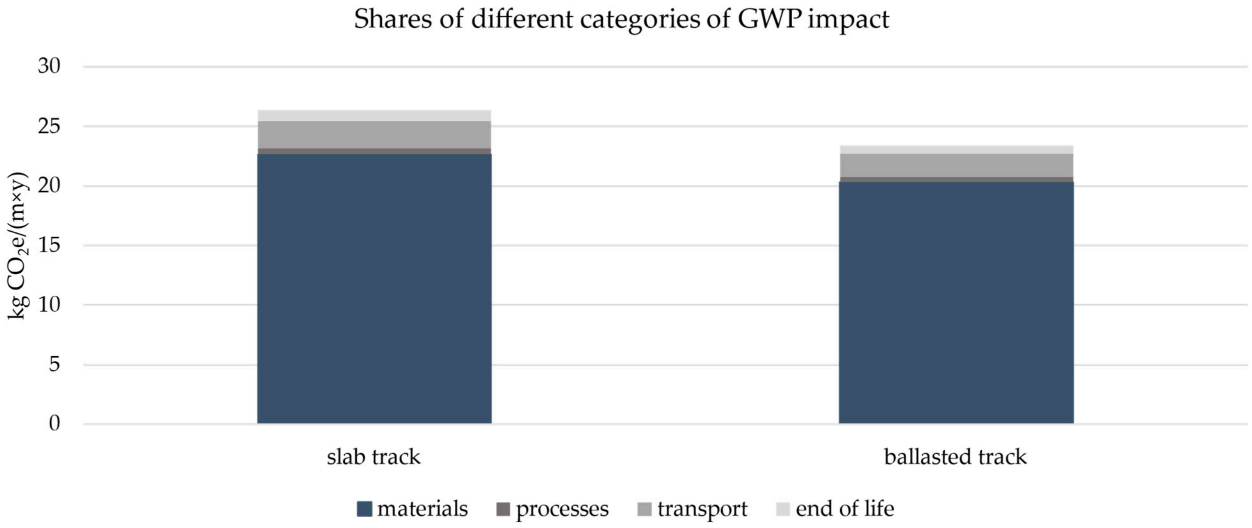


Figure 6. Shares of different categories (materials, processes, transport, and end of life) in the total relative GWP impact for slab and ballast track for the standard scenario.

4. Discussion

As seen in the results, slab track shows higher GHG emissions for open track. The difference increases with lower quality of subsoil condition. This is due to the fact that slab track has a rigid superstructure resulting in higher longevity but lower maintainability in case of heterogenous settlements. Therefore, a settlement-free substructure is crucial for slab track application resulting in more extensive measures for soil reinforcements in case of medium or bad preexisting soil conditions.

Within tunnel areas, the reverse effect can be seen due to less need for soil reinforcements because of the already settlement-free tunnel sole. Since slab track (less to no maintainability in case of settlements) has higher demands on its supporting layers, this has more positive effects on slab track than for ballasted track. This is also in line with the findings of Hausberger et al. [18], who analyzed different types of superstructure for the boundary conditions of the Brenner Base Tunnel and concluded that slab track shows lower GHG emissions in tunnel areas.

Olugbenga et al. [7] reviewed over 100 studies for embodied carbon emissions of railway track within the production phase, resulting in a statistical model delivering a range of 941 (±168) tCO_2eq per kilometer. In the present study, the railway track production phase (A1–A5), considering optimal preexisting soil conditions, amounts to 651 tCO_2eq per kilometer for ballasted track and 1197 tCO_2eq per kilometer for slab track. This clearly shows that the base scenario is comparable to other studies. The variation in preexisting soil conditions was assessed in the present study for the first time, which is why there is no possibility for comparing results.

In order to improve the understanding of the results, sensitivity analyses were carried out. Figure 7 shows the required extension of service life for the slab track for the open track scenarios with the best, medium, and bad soil conditions so as to balance the yearly GWP impact of ballasted track. The service life of slab track needs to exceed 73 years to become the preferred construction for all scenarios.

Based on these findings, saving potentials for GHG emissions can be identified. Mainly, they can be found in the production phase of the materials.

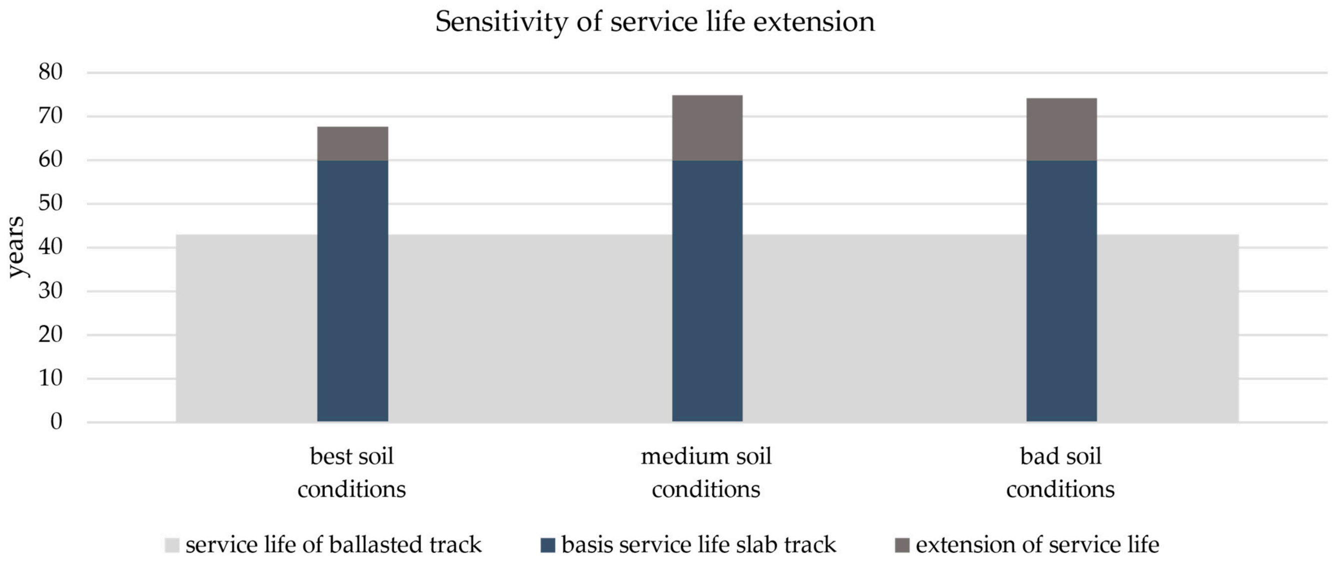


Figure 7. Sensitivity analysis of the service life of the slab track depending on the subsoil condition (different scenarios).

5. Conclusions

In conclusion, this study presents a comparison between slab and ballasted track considering different preexisting soil conditions based on lifecycle assessments. The main findings can be summarized as follows:

- Ballasted track produces lower CO_2 emissions than slab track in all scenarios for open track (optimum soil condition, medium soil condition, bad soil condition) ranging from 11–20%.
- Bad preexisting soil conditions increase LC GHG emissions by 26%, underlying the necessity to integrate this parameter into the lifecycle assessment of railway tracks.
- The critical service life of slab required to balance the emissions of ballasted track for all scenarios is 73 years.
- In tunnel areas with a preexisting concrete sole, slab track application shows lower LC GHG emissions by 4%.
- For both construction types, over 80% of the GHG emissions stem from material production.

Limitations include the fact that the results can differ in other countries, especially during the use phase. Service life of components (e.g., ballast) very much depends on ballast quality, dewatering system, and substructure quality, which may lead to the need for ballast cleaning or component exchange for ballasted track during its service life. Also, as stated, maximum design speed in Austria is 250 km/h. Thus, results may differ for higher design speeds.

As more than 80% of the GWP impact stems from the production phase of the materials, this is the highest potential for mitigation of environmental impacts. For this reason, it is crucially important to improve concrete and steel production processes to reduce CO_2 emissions. Several approaches can be taken, such as partially or totally replacing the cement with fly ash [38] in concrete production, using bauxite industry tailings for cement production [39], or using sulfur instead of cement [40]. Also, filler material for intermediate layers shows significant CO_2 reduction potential, for example, by using waste products from asphalt production [41,42]. Steel production facilities are also aiming to transition to processes with lower CO_2 emissions. By using the EAF process (electric arc furnace), more than 60% of CO_2 emissions can be avoided compared to using the BOF process (blast oxygen furnace) [43]. In addition, the proportion of scrap can be increased, which allows for a higher percentage of reuse of materials. This principle can be applied not only to steel but also to other materials. Wherever possible, materials should be reused directly on the construction site. On the one hand, this reduces the number of raw materials needed and, on the other hand, it reduces the number of materials that need to be transported to and from the construction site. The use of a ballast bed cleaning machine provides an example of this, as these machines usually reuse half of the ballast during the renewal process.

Another way to reduce CO_2 is to increase the transport efficiency due to the large masses of material required for track construction. This means that transport distances should be kept short, and efficient means of transport such as rail freight should be used. The same approach applies to construction processes and logistics where optimization in deployment strategy can reduce transport lengths. Other GHG emission reduction potentials can be achieved by substituting diesel with alternative energy carriers (e.g., alternative fuels such as HVO) or, in general, to use other technologies that enable the hybridization or electrification of machinery [37].

This study helps practitioners and design engineers to identify the optimal track design based on actual in situ coil conditions, whereas previous studies assume optimal subsoil conditions. Including varying preexisting soil conditions is crucial, evidenced by our finding that bad subsoil conditions increase LC GHG emissions by 26%.

Author Contributions: Conceptualization, D.K. and M.L.; methodology, D.K. and M.L.; validation, D.K. and M.L.; formal analysis, D.K. and M.L.; investigation, D.K.; resources, D.K. and M.L.; data curation, D.K.; writing—original draft preparation, D.K. and M.L.; writing—review and editing, D.K. and M.L.; visualization, D.K.; supervision, M.L.; project administration, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: Open access funding by Graz University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Commission on Environment and Development. *Our Common Future*; Oxford University Press: Oxford, UK; New York, NY, USA, 1987; ISBN 978-0-19-282080-8.
2. European Environmental Agency Greenhouse Gas Emissions from Transport in Europe. Available online: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (accessed on 14 August 2023).
3. Facanha, C.; Horvath, A. Evaluation of Life-Cycle Air Emission Factors of Freight Transportation. *Environ. Sci. Technol.* **2007**, *41*, 7138–7144. [CrossRef] [PubMed]
4. Chester, M.; Horvath, A. *Environmental Life-Cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air*; University of California: Berkeley, CA, USA, 2007.
5. Olugbenga, O.; Kalyviotis, N.; Saxe, S. Embodied Emissions in Rail Infrastructure: A Critical Literature Review. *Environ. Res. Lett.* **2019**, *14*. [CrossRef]
6. Landgraf, M.; Horvath, A. Embodied Greenhouse Gas Assessment of Railway Infrastructure: The Case of Austria. *Environ. Res. Infrastruct. Sustain.* **2021**, *1*, 025008. [CrossRef]
7. Landgraf, M.; Zeiner, M.; Knabl, D.; Corman, F. Environmental Impacts and Associated Costs of Railway Turnouts Based on Austrian Data. *Transp. Res. Part D Transp. Environ.* **2022**, *103*, 103168. [CrossRef]
8. European Commission. *Statistical Pocketbook 2021—EU Transport in Figures*; European Commission: Brussels, Belgium, 2021.
9. Michas, G. Slab Track Systems for High-Speed Railways, KTH: Stockholm, Sweden, 2012.
10. Esveld, C. *Modern Railway Track*; MRT Productions: Ho Chi Minh City, Vietnam, 2001.
11. Darr, E.; Fiebig, W. *Feste Fahrbahn—Konstruktion, Bauarten, Systemvergleich Feste Fahrbahn-Schotteroberbau*; VDEI, Ed.; Tetzlaff Verlag GmbH & Co. KG: Hamburg, Germany, 1999; ISBN 3-87814-700-7.
12. Bastin, R. Development of German Non-Ballasted Track Forms. *Proc. Inst. Civil Eng. Transp.* **2006**, *159*, 25–39. [CrossRef]
13. SSF Ingenieure AG. Ballastless Track on High-Speed Lines A Guarantee for Travel Savety and Comfort. Available online: https://www.ssf-ing.de/fileadmin/web_data/Downloads/Broschueren/Englisch/Feste_Fahrbahn_Ballastless_track__EN.pdf (accessed on 21 July 2023).
14. Lichtberger, B. *Track Compendium*, 1st ed.; DVV Media Group GmbH I Eurailpress: Hamburg, Germany, 2005; ISBN 3-7771-0320-9.

15. *EN 15804:2012+A2:2019 + AC:2021 2022*; Beuth Verlag GmbH Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. German Version; Comite Europeen de Normalisation: Bruxelles, Belgium, 2021.
16. 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]
17. Kiani, M.; Parry, T.; Ceney, H. Environmental Life-Cycle Assessment of Railway Track Beds. *Proc. Inst. Civil Eng. Eng. Sustain.* **2008**, *161*, 135–142. [CrossRef]
18. 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]
19. Hansen, L.; Öztürk, L.S.I.; Milius, B. CO_2-Emissionen Beim Einbau: Feste Fahrbahn Im Vergleich Zum Schotteroberbau. *EI-Eisenbahningenieur* **2023**, *6*, 59–63.
20. Marschnig, S. *Innovative Track Access Charges*; TU Graz: Styria, Austria, 2016.
21. Marschnig, S.; Veit, P. Assessing Average Maintenance Frequencies and Service Lives of Railway Tracks: The Standard Element Approach. In *New Research on Railway Engineering and Transport*; Hessami, A., Muttram, R., Eds.; IntechOpen: London, UK, 2023.
22. voestalpine Schiene GmbH Environmental Product Declaration—Rails for High-Speed Railways, Mixed Railways, Heavy Loads, Urban Public Transportation, Crane and Construction Rails 2019. Available online: https://www.epd-norge.no/epder/mutual-recognition-epd-fra-andre-programoperatorer/rails-for-high-speed-railways-mixed-railways-heavy-loads-urban-public-transportation-crane-and-construction-rails (accessed on 21 July 2023).
23. Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen ÖKOBAUDAT Informationsportal Nachhaltiges Bauen. Available online: https://www.oekobaudat.de/ (accessed on 21 July 2023).
24. InformationsZentrum Beton GmbH Umweltproduktdeklarationen—Beton.org. Available online: https://www.beton.org/betonbau/planungshilfen/umweltproduktdeklarationen/ (accessed on 14 August 2023).
25. Stahl- und Walzwerk Marienhütte, G.m.b.H. *Environmental Product Declaration—Betonstahl*; Stahl- und Walzwerk Marienhütte G.m.b.H: Graz, Austria, 2020.
26. DB Netz AG Ausbaustrecke Oldenburg–Wilhelmshaven Planfeststellungsabschnitt Varel–Sande (PFA 4) Ausbauabschnitt 4.2 Bahnhof Sande 2019. Available online: https://bauprojekte.deutschebahn.com/media/projects/7301/docs/BR_oldenburg-wilhelmshaven-varel-sande-pfa-4-1-201906.pdf (accessed on 21 July 2023).
27. Eyerer, P.; Reinhardt, H.-W. *Ökologische Bilanzierung von Baustoffen Und Gebäuden*; Birkhäuser: Basel, Switzerland, 2000.
28. Bundesministerium für Klimaschutz. Umwelt, Energie, Mobilität, I. und T. *Emissionskennzahlen Datenbasis 2020*. 2022. Available online: https://www.umweltbundesamt.at/fileadmin/site/themen/mobilitaet/daten/ekz_pkm_tkm_verkehrsmittel.pdf (accessed on 21 July 2023).
29. Gräbe, P.; Mtshotana, B.; Sebati, M.; Thünemann, E. The Effects of Under-Sleeper Pads on Sleeper-Ballast Interaction. *J. S. Afr. Inst. Civ. Eng.* **2016**, *58*, 35–41. [CrossRef]
30. Freudenstein, S.; Iliev, D.; Ahmad, N. Die Kontaktspannung zwischen elastisch besohlten Schwellen und Schotter: Moderner Gleisbau und Instandhaltung. *ETR Eisenbahntech. Rundsch* **2011**, *60*, 13–20.
31. Veit, P.; Marschnig, S. Technische Und Wirtschaftliche Aspekte Zum Thema Schwellenbesohlung—Teil 2: Wirtschaftlichkeit Im Netz Der ÖBB. *ZEVRail* **2009**, *133*. Available online: https://www.zevrail.de/artikel/technische-und-wirtschaftliche-aspekte-zum-thema-schwellenbesohlung-teil-2 (accessed on 21 July 2023).
32. Neuhold, J.; Landgraf, M. Effects of Under-Sleeper-Pads on Long-Term Track Quality Behaviour. In Proceedings of the Road and Rail Infrastructure, Zagreb, Croatia, 17 May 2018; pp. 675–681.
33. Slab Track Austria Team Porr Bau GmbH Slab Track Austria. Available online: https://slabtrackaustria.com/ (accessed on 4 May 2023).
34. Krammer, C. "Mud-Pumping" Im Eisenbahnbau: Labortechnische Untersuchungen Der Trennstabilität Zwischen Unterböden Aus Schluff-Sand-Gemischen Und Gleisschotter Unter Dynamischen Vertikallasten. Ph.D. Thesis, Technische Universität Graz, Graz, Austria, 2020.
35. *AG 09.02*; Tragschichten, Gestaltung Der Randbereiche Einschließlich Kabeltroglagen. ÖBB-Infrastruktur: Vienna, Austria, 2014.
36. *AG B 50*; Teil 1 Oberbauformen. ÖBB-Infrastruktur: Vienna, Austria, 2009.
37. Zeiner, M.; Landgraf, M.; Knabl, D.; Antony, B.; Cárdenas, V.B.; Koczwara, C. Assessment and Recommendations for a Fossil Free Future for Track Work Machinery. *Sustainability* **2021**, *13*, 11444. [CrossRef]
38. Suhendro, B. Toward Green Concrete for Better Sustainable Environment. *Procedia Eng.* **2014**, *95*, 305–320. [CrossRef]
39. Negrão, L.B.A.; Pöllmann, H.; Costa, M.L. da Production of Low-CO_2 Cements Using Abundant Bauxite Overburden "Belterra Clay". *Sustain. Mater. Technol.* **2021**, *29*, e00299. [CrossRef]
40. Fediuk, R.; Mugahed Amran, Y.H.; Mosaberpanah, M.A.; Danish, A.; El-Zeadani, M.; Klyuev, S.V.; Vatin, N. A Critical Review on the Properties and Applications of Sulfur-Based Concrete. *Materials* **2020**, *13*, 4712. [CrossRef]
41. Tarbay, E.W.; Azam, A.M.; El-Badawy, S.M. Waste Materials and By-Products as Mineral Fillers in Asphalt Mixtures. *Innov. Infrastruct. Solut.* **2018**, *4*, 5. [CrossRef]

42. Awed, A.M.; Tarbay, E.W.; El-Badawy, S.M.; Azam, A.M. Performance Characteristics of Asphalt Mixtures with Industrial Waste/by-Product Materials as Mineral Fillers under Static and Cyclic Loading. *Road Mater. Pavement Des.* **2022**, *23*, 335–357. [CrossRef]
43. Burchart-Korol, D. Life Cycle Assessment of Steel Production in Poland: A Case Study. *J. Clean. Prod.* **2013**, *54*, 235–243. [CrossRef]