



Selection of track form in railway tunnel from a life cycle analysis perspective

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Received: 11 December 2023 / Revised: 28 May 2024 / Accepted: 11 July 2024
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Abstract

The use of greenhouse gas (GHG) emissions as a criterion for decision-making within the rail industry is increasing. The demand for considering this criterion affects the type of decision models acceptable by railway infrastructure managers in the planning, construction, and maintenance of railway assets. The total amount of GHG emitted from a track solution in tunnels during its service life depends on the track form (i.e., ballasted track or ballastless track), the type of construction, maintenance machines used, current traffic profile, and tunnel length. However, the development in the design of ballastless track systems during recent decades to make them environmentally friendly motivates infrastructure managers to rethink and consider the use of the system. This study examines the effect of several design and maintenance factors not adequately addressed in previous research. These factors are (i) the modulus of elasticity of track support affecting the design of track forms, (ii) differences in maintenance and renewal required for track forms in the corresponding line condition, and (iii) recent developments in optimizing the environmental impact of ballastless tracks. The GHG emissions, represented by life cycle carbon dioxide equivalent (CO₂e) emissions, are calculated using the climate impact software developed by

the Swedish Transport Administration Trafikverket. The result is compared with the estimated emission from the conventional ballasted tracks. The method proposed in this paper is applied in a case study to study the effect of applying the optimized ballastless track system Rheda 2000[®] in a railway tunnel (the Hallsberg-Stenkumla tunnel) as part of a new line project in Sweden. The model applied in the study is an integral part of an integrated decision support system for effectively selecting track solutions from a lifecycle perspective. The study's findings are: (i) the life cycle CO₂ equivalent emissions by a ballastless track during its life cycle are 10% lower than that of the ballasted track, (ii) the primary total emission driver for both track form solutions is the emissions generated at the manufacturing of rails, (iii) the second important emission factor for the ballasted track solution is the emission from the renewal of the track form during its life cycle, and (iv) the second important emission factor for the ballastless track solution is concrete manufacturing.

Keywords Ballastless track · Greenhouse gas emission · Railway tunnel · Decision support system

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1 Introduction

The rail infrastructure is one of the challenging technical systems for which the Swedish Transport Administration implements thorough planning and managerial control. As a vital part contributing to infrastructure effectiveness, rail track assets aim to ensure proper availability and economic profitability, influencing the selection of type and configuration of track solutions. However, sustainable development challenges and current research have recently brought a deeper understanding of track assets' environmental impact [1]. Ecological friendliness has become an increasingly influencing criterion when selecting track solutions [2], [3]. One of the negative environmental impacts of track assets

is life cycle GHG emission, represented by life cycle CO₂e emission. Despite the problem's complexity, reducing CO₂e emissions is a recognized challenge humanity must solve shortly [4].

In this article, two construction types of railway tracks are referred to as track forms: the ballasted track and the ballastless track. When considering the track forms from the structural point of view, the primary difference between them is the presence and absence of some components in the track structure. The ballast layer and relatively low content of concrete and steel in the ballasted track structure distinguish it from the ballastless track structure, which has a high content of steel and concrete while lacking ballast.

Researchers have differing views on which track form results in higher life cycle CO₂e emissions. Zandi et al. argued that the emission from a ballastless track is more significant than from a ballasted track; the main reason for this is the higher percentage of concrete and steel in the ballastless track structure [2].

Milford and Allwood investigated the life cycle CO₂e emission generated by four types of tracks. They revealed that at moderate traffic loads, the process and maintenance emissions of the double-headed embedded track are lower than those of the double-headed conventional track [5]. Pons et al. evaluated the environmental impact of the track forms in 18 impact categories. They revealed that CO₂ equivalent emissions of ballasted tracks are lower for service life up to 50, 75, and 100 years [6]. Biancardo et al. pointed out a higher environmental friendliness of the ballastless track than the ballasted one [3]. The authors argued that a higher environmental impact of the ballasted track depends on the less available ballast of proper characteristics and increased raw material use compared to the readily available concrete track plate in the ballastless track.

Previous research has not adequately addressed the following issues in the estimation of life cycle CO₂e emissions in their studies: (i) the modulus of elasticity of track support affecting the design and service life of track components, (ii) differences in maintenance and renewal required for track forms in the corresponding line condition, and (iii) recent developments in optimizing the environmental impact of ballastless tracks. The current study aims to address the abovementioned issues in the revealing relationship between the types of track forms, their design, maintenance, and renewal needs, operating conditions, and their CO₂ equivalent emissions during the life cycle. The most important parameters for assessing the life cycle CO₂e emission are the emissions generated by transporting tunnel rock material, manufacturing of track components, and construction, maintenance, and renewal of the track asset. This article presents the result of the study of the life-cycle CO₂e

emissions of the ballastless track solution compared to the ballasted one using the Swedish railway tunnel case.

When comparing this research work with existing research, it is worth noting the following. Firstly, the applied methodological approach is the consequential approach, which allows for assessing the impact of track assets on global environmental loads. On the contrary, several previous studies used the attributional approach to assess what part of the global environmental loads should be assigned to the track asset [7], [8]. Additionally, the scope of the current study encompasses all feasible life cycle phases of the investigated track asset (except for the demolition phase). This implies assessing the CO₂e emissions generated from material extraction, track construction, maintenance, and renewal corresponding to the case study's conditions. The assessment in some previous studies did not consider all life cycle phases [9]. Furthermore, several previous studies did not thoroughly consider the maintenance phase as a source of CO₂e emissions. Essential traffic conditions are not considered a factor in maintenance. Moreover, some of the crucial parts of the track asset from a maintenance perspective, which generated significant CO₂e emissions, i.e., track transitions and track support structure, were not considered in previous studies. Finally, previous studies did not focus on the most promising findings in developing environmentally friendly designs for ballastless tracks. The current study addresses these gaps to contribute to reducing life cycle CO₂e emissions.

This article is an extension of the conference paper titled "Selection of Track Solution in Railway Tunnel: Aspect of Greenhouse Gas Emission" [10], presented at the International Congress and Workshop on Industrial Artificial Intelligence in 2023. Additional content of this study includes a description of the standard LCA approach and its adaptation to create a customized LCA methodology for the current case study. Further, parametric study and sensitivity analysis have been added to the initial study to improve the understanding of the relationship between track design and life cycle carbon emissions. This provides information about the most significant factors that can influence the selection of track form for the case study.

2 Method

Figure 1 presents the workflow of the main activities carried out in this study and explains it in the subsequent sub-sections.

Fig. 1 The flow chart outlines the essential activities in the study

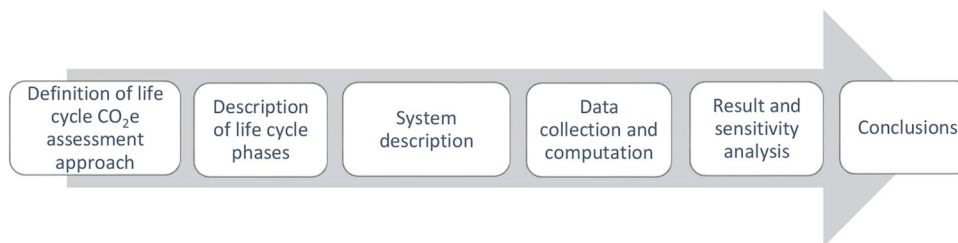
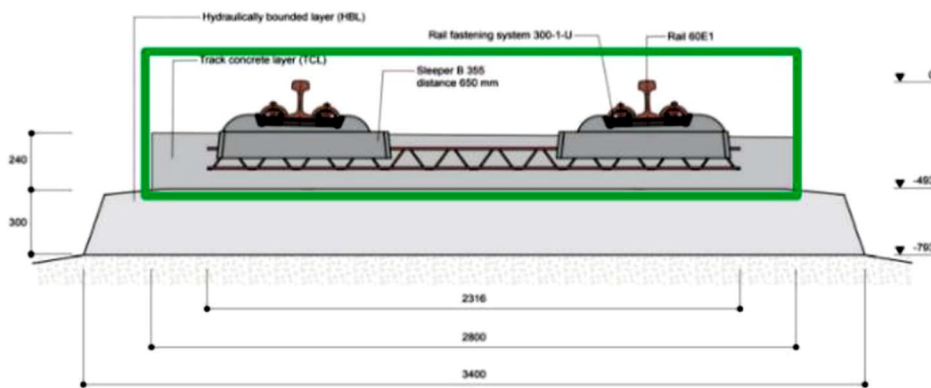


Fig. 2 Rheda 2000 Green ballastless track system by Rail One (The green-contoured area designates the calculated part of the system). (Rail One)



2.1 Study approach

The approach implemented is a bottom-up approach previously used in research related to life cycle assessment (LCA) [2], [11]. This approach allows for assessing the environmental impact of a system using deep knowledge of its life cycle demands. Implementing the approach, we focused on one specific railway infrastructure asset type: a rock tunnel track asset. An LCA assessment can be carried out using two methodological approaches – attributional and consequential. The attributional approach considers which part of the global environmental loads should be assigned to the system. In the current study, the authors aim to identify the reduction potential for life cycle CO₂e emissions. In this concern, the consequential approach is used in the current study, and the impact of the case study system on environmental loads is considered.

The life cycle CO₂e emissions studied are for (i) the transportation of rock material produced by the excavation of a 4.8 km double-pipe railway rock tunnel along the Hallsberg - Stenkumla line in Sweden, (ii) the construction, maintenance, and renewal of the Rheda 2000 Green ballastless track system during the tunnel operating time. The life cycle CO₂e emissions from the track system were calculated for the design without the hydraulically bounded layer (HBL) (see the green-contoured area in Fig. 2), and considering the relevant traffic conditions, the estimated service life of the track elements and the complex of works for the construction, maintenance, and renewal of the ballastless track in the tunnel. In this study, a similar calculation for

a ballasted track solution in the tunnel was performed. The life cycle CO₂e emissions from the ballastless and ballasted track solutions in the tunnel were compared to reveal the dependence of a track asset's life cycle CO₂e emissions on the type of its track form.

2.2 Standard LCA approach

The standard life cycle assessment (LCA) approach is built on the principles described in ISO 14040:2006 [12]. It encompasses six modules of life cycle stages, i.e., (i) pre-design phase, (ii) product phase, (iii) construction phase, (iv) operation phase, (v) disposal, and (vi) other relevant information such as machinery environmental impact, etc. The modules, in turn, are divided into several life cycle stages, which are set depending on the assessment's character. Table 1 presents the standard LCA structure, including modules and life cycle stages.

The standard LCA approach requires that the criteria for selecting life cycle stages and the models used are described and motivated. The life cycle stages depend on the assessment's character and can be modified to create an adapted LCA.

2.3 Data collection

All data collected for the current study fall into two subcategories: (i) general data required by the climate impact calculation tool (CICT) developed by the Swedish Transport Administration [13] and (ii) system-specific data related to

Table 1 The modules and associated life cycle stages for assessing a product's or service's environmental impacts according to the standard LCA in ISO 14040:2006

Module	Life cycle stage	
A0 Pre-design phase	A0	Feasibility Study
A1-A3 Product phase	A1	Acquisition of raw materials
	A2	Transportation
	A3	Production
A4-A5 Construction phase	A4	Transportation
	A5	Construction and installation
B1-B8 Use phase	B1	Use
	B2	Maintenance
	B3	Refurbishment
	B4	Replacement
	B5	Renewal
	B6	Operating energy
	B7	Other operating processes
	B8	Users' energy use
C1-C4 Final phase	C1	Dismantling, demolition
	C2	Transportation
	C3	Recovery of used product
	C4	Disposal
D Operations beyond system boundaries	For instance, lighting and heating	

the case study-specific conditions. Input data for the first subcategory include the quantities of geotechnical works, raw materials, track components, and the pre-installed CO₂e emission factors for these factors. Standardized emission-related measures associated with the construction, maintenance, and renewal works adopted by the Swedish Transport Administration were used. The second subcategory encompasses the expected life cycle behavior of the Rheda 2000[®] Green ballastless track system in the study case, i.e., the quantitative values of corresponding design elements and emission-related construction, maintenance, and renewal works required for the Rheda 2000[®] Green system in the Hallsberg - Stenkumla tunnel.

The data collection method includes gathering basic data and filling data gaps. The primary data were collected by completing the data request in CICT; the basic quantitative values were obtained using the system's selected boundaries. The missing data related to the ballastless track system design was gathered; information from research databases and the experts and designers at RailOne, the developer and manufacturer of Rheda 2000[®] Green, was obtained.

2.4 Computation of CO₂e emission

CO₂e emissions were computed using the climate impact calculation tool CICT, software based on the standard LCA principles and framework.

The computational complexity of the approach used in this paper is simple-moderate, depending on the size of the

system and the number of parameters in question. The complexity is considered to be similar to existing works in literature since the tool used has implemented a standard CO₂e computational approach.

The applied logical order of calculation is as follows.

- The emissions of CO₂e from the transportation of rock material from the tunnel's construction have been calculated. The amount of rock material was estimated as a function of the tunnel cross-section. CO₂e from tunneling and excavation are not included.
- The CO₂e from the construction of the track solution includes the emissions during (i) the "cradle-to-grave" of the track components, i.e., from the extraction of raw material to the finished product, (ii) the construction of the track system, and (iii) transport of the material and components.
- The CO₂e for the operation phase encompasses the emissions from maintenance and renewal of the track during the estimated service life of the tunnel considered by a pessimistic life cycle scenario presented in Sect. 3.3. According to the Swedish Transport Administration's experiences and using the principles of the standard element model developed at the Graz University of Technology [11], the frequencies for maintenance and renewal work for the ballasted track in the tunnel concerning the line traffic conditions were established. A similar set was selected for the Rheda 2000 Green system. Meanwhile, the system's design was assimilated for the Hallsberg – Stenkumla tunnel conditions. A series of design-adapting workshops with the system designers was conducted.
- The computation did not include the CO₂e emissions from the final stage phase phase. This is because of the lack of knowledge about demolishing the ballastless tracks.
- Within the module of other environmental information, the Hallsberg-Stenkumla project's conditions influencing CO₂e emissions were regarded in the computation. Some of these concerns the line's traffic conditions, the productivity of the applied machinery, and diesel consumption by this machinery during construction and maintenance.
- Emissions in modules for the respective track solutions were combined into a total emission value of the considered track solution using the formula below. Then, the main CO₂e emission drivers for each track form were determined.

$$Total\ CO_2e_{equivalent} = \sum_{t=1}^T \sum_{n=1}^N X_{tn}$$

Where t is the period or lifecycle phase, n is lifecycle activities, and X_m is the CO₂e emissions associated with activity N occurring during period t . T is the calculation period, while N is the track system's total number of life activities.

3 Use case

3.1 Description of the line

The New double-track line between Hallsberg and Stenkumla lies in Örebro county and connects the Hallsberg railway yard with the new double-track asset in Stenkumla. The tracks go through a double-pipe railway tunnel along the section Km 7 to Km 9. The line is dedicated to mixed traffic. The expected growth in annual tonnage within 15 years from the start of operation will be approximately 10 million gross tons (MGT) over the period. Table 2 presents the characteristics of the line's traffic conditions.

3.2 Track solutions

3.2.1 The ballastless track system rheda 2000® green

A ballastless track includes rails and rail fastenings that are either directly attached to a prefabricated concrete track slab, also called the track concrete layer (TCL), or lie on prefabricated concrete elements poured into an in-situ TCL alternatively placed on this. The natural modulus of elasticity of the tunnel bottom has influenced the design of ballastless track systems in tunnels. Recent design optimization of the ballastless track system Rheda 2000® has led to the appearance of the environmentally-friendly version called Rheda 2000® Green (see Fig. 3). The system adapted for the Hallsberg - Stenkumla tunnel has a construction height of 0.68 m from the tunnel floor to the top of the rail (TOR). The design of the system is characterized by optimized dimensions, the lack of longitudinal reinforcement in TCL, and its plastic fiber reinforcement. Additionally, in TCL, instead of cement type CEM I (clinker percentage 95–100%), cement type CEM II is provided (reduced clinker content to 65%).

Table 2 The technical specification of traffic conditions on the Hallsberg – Stenkumla line

Parameter	Unit	Value
Axle load	ton	25
Design speed	kph	200
Track curve radii in the tunnel U2/N2	m	2 880/2 860
Max slope in the tunnel	‰	10
Annual passed tonnage	MGT	23
Expected annual passed tonnage	MGT	33

These measures reduced the system's life cycle CO₂e emissions by 31% [14].

3.2.2 Track transitions

A ballastless track solution in the tunnel requires a track transition solution at each tunnel port to connect to the surrounding ballasted track. This transition solution, referred to in this study as track transition, is designed to achieve a controlled stiffness change between the "hard" ballast-free track and the "soft" ballast track. It makes it possible to keep the value of the dynamic forces arising in the track structure and the interfaces within permitted tolerances. In this study, the CO₂e emission of the transitions is included in the ballastless track calculation. Figure 4 visualizes the typical design of track transition between the ballasted track and the ballastless track system Rheda 2000®.

The track transition is composed of three zones characterized by different global stiffness. In the superstructure, this is achieved by using specifically designed wide sleepers along all the zones and additional auxiliary rails along Zone 1 and Zone 2, counteracting the settlement mechanism in track transition. The substructure of the track transition contains a concrete transition plate. The total length of the transition is 36 m.

3.2.3 The ballasted track

The conventional ballasted track consists of a layer of ballast placed on a leveling layer of sub-ballast. On the ballast lay concrete or wooden sleepers to which the rails are attached. The ballasted track design in tunnels is specific due to the natural modulus of elasticity of the tunnel bottom. To reduce the ballast deterioration rate, the track design in tunnels includes an enlarged thickness of the ballast layer and sub-ballast layer. In this study, the ballasted track solution has a construction height of 1.60 m from the tunnel bottom to TOR. This construction height, according to the current regulation of the Swedish Transport Administration, consists of 0,4 m between TOR and the bottom of the sleeper, 0,4 m of ballast under the bottom of the sleeper, and 0,8 m of sub-ballast.

3.3 Characteristics of the tunnel

The Hallsberg-Stenkumla tunnel is a rock double-pipe railway tunnel with four cross-service tunnels every 500 m. According to the project's System Requirement Document, the tunnel construction will generate a rock material of 374 000 m³.

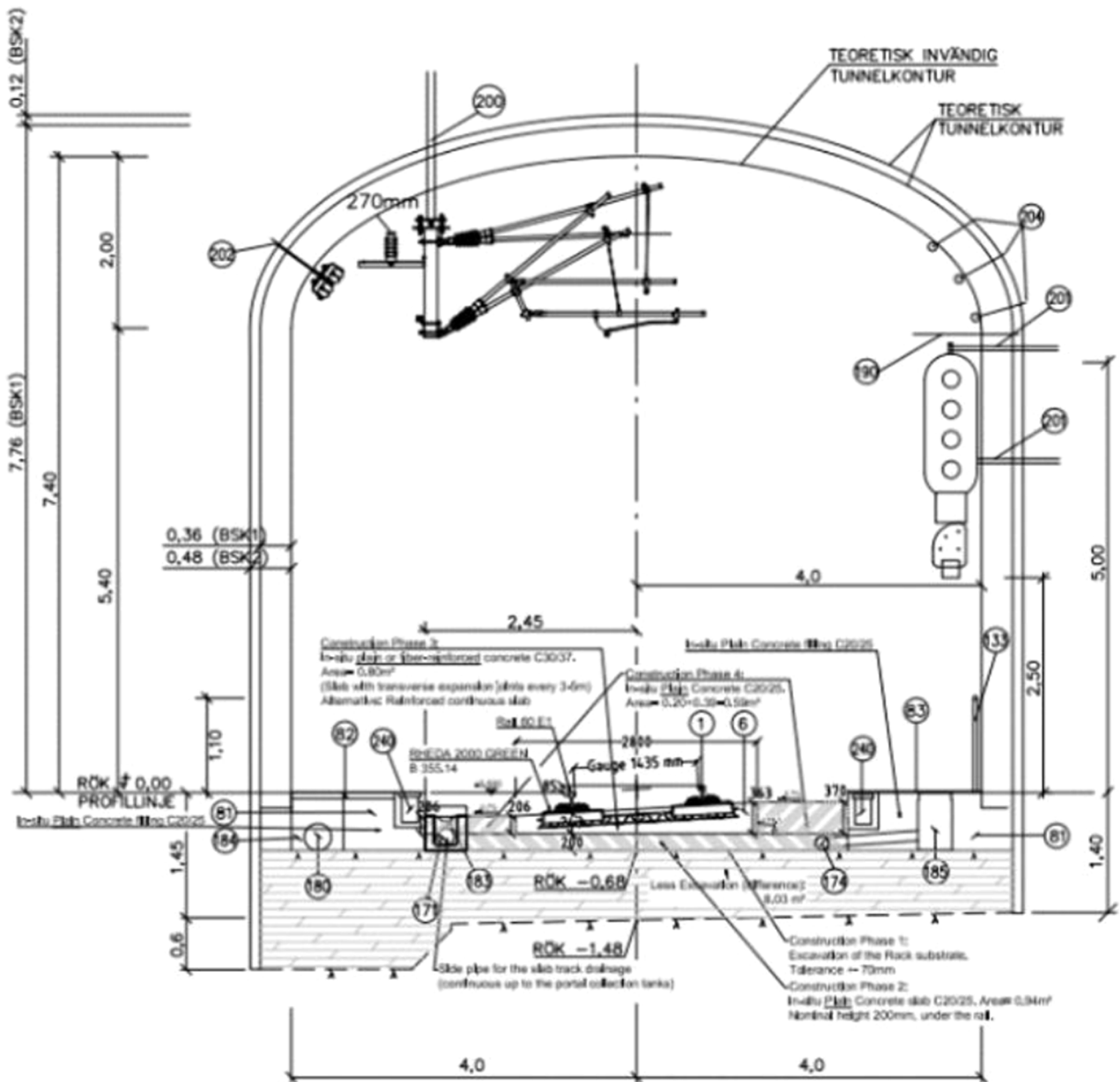


Fig. 3 Cross-section Rheda 2000 Green in the Hallsberg - Stenkumla tunnel, curved track (Rail One)

3.4 Service Life of the system

In the current study, the estimation of the life cycle CO₂e emissions includes the emissions generated by the transport of rock material gained by the tunnel construction and the life cycle CO₂e emission from the track asset in the tunnel. The system's service life, i.e., the tunnel's load-bearing system and the track asset inside, is estimated by the "worst-case" scenario. The latter means an intentionally shortened service life to estimate the life-cycle behavior of the system concerning the following:

- current and expected traffic conditions, and.
- relevant infrastructure regulations.
- common service life risks of the system.

The passed tonnage determines the lifetime of track components. The reference values of the passed tonnage indicating component change are partly taken from the Swedish Transport Administration's experience and partly from scientific sources. Then, the service life duration was recalculated for the critical track components considering (i) the expected traffic volume, (ii) the ratio of the passenger and freight

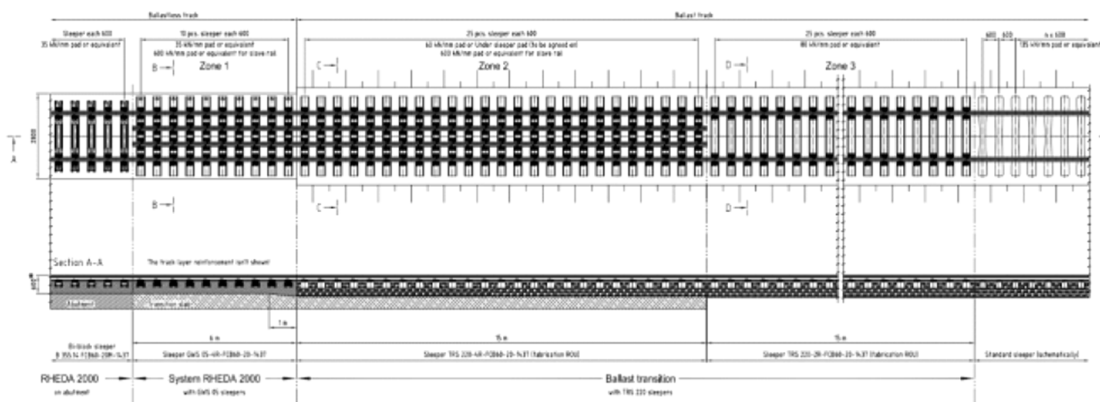


Fig. 4 Typical track transition between the ballastless track system Rheda 2000 and the ballasted track (Rail One)

Table 3 Estimated economical service life of the Hallsberg – Stenkumla tunnel track solutions

	Sub-system		
	Tunnel	Ballastless track	Ballasted track
Economical service life, years	100	50	30

trains, and (iii) the tunnel conditions affecting dynamic behavior and rate of deterioration of track components. In this study, the critical track component’s life determines the track form’s life. For a ballasted track, this component is the ballast; for a ballastless track, it is TCL. Further, in this study, the critical track component’s life corresponds to the track form’s economic service life, and the latter is a period until the optimal balance between maintenance and reinvestment is achieved. The estimated economical service life for the tunnel and the track solutions is presented in Table 3.

3.5 System boundary

According to Fig. 3, the system boundary for calculating life cycle CO₂e emissions is chosen in this study to lie between zone 2 and zone 3. The length of the track section between the system boundary points at the respective tunnel ports is 2,400 m (4,800 m in total).

The computation includes new construction, emission-related maintenance activities, and all renovation measures (incl. all materials) required for a track solution of 4,800 m in a rock tunnel over 100 years. Emission-related maintenance activities in this study refer to using larger machines and heavier equipment and involve a significant climate impact. The life cycle CO₂e emission from the track transitions is included in the computation of the ballastless track solution. Besides the track system, the computation does not include any installations in the tunnel.

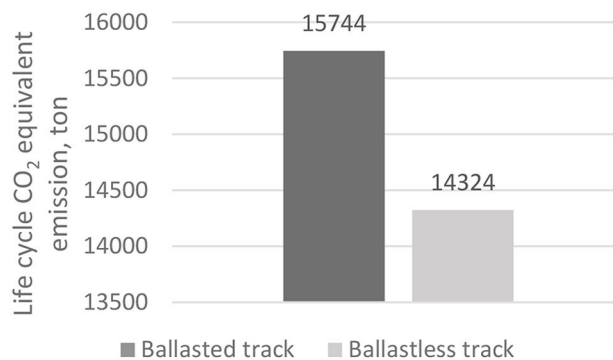


Fig. 5 The life cycle CO₂e emission for the ballasted and ballastless track solutions

4 Results and discussion

4.1 Distribution of the life cycle CO₂e emissions

The calculations show that the CO₂e emissions from the construction of the tunnel and the maintenance and renewal of the track asset are approximately 1,420 tons (approx. 10%) higher for the ballasted track than for the ballastless track during its lifetime, with the conditions for the life cycle analysis in this study. Figure 5 shows that the life cycle emissions for the ballasted track are 15,744 tons of CO₂e and 14,324 tons of CO₂e for the ballastless track, including the track transitions.

The most significant ballasted track emission items are the emissions generated by the manufacturing of rails (hot dip galvanized steel), diesel consumption for performing renewal works, transport of the tunnel rock material, and removed ballast (illustrated in Fig. 6 as diesel). Other emission sources are the manufacturing of sleepers, fastenings, and explosives. Figure 6 presents the distribution of the emissions sources for the track solution with ballast.

As presented in Fig. 7, the ballastless track solution generates the most emissions from rail manufacturing. The next

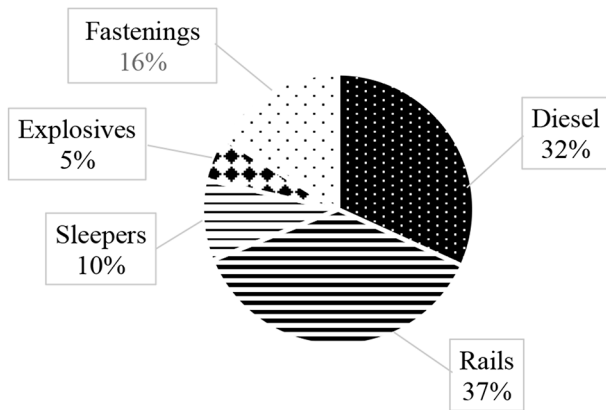


Fig. 6 Distribution of the life cycle CO₂e emission items for the ballasted track solution

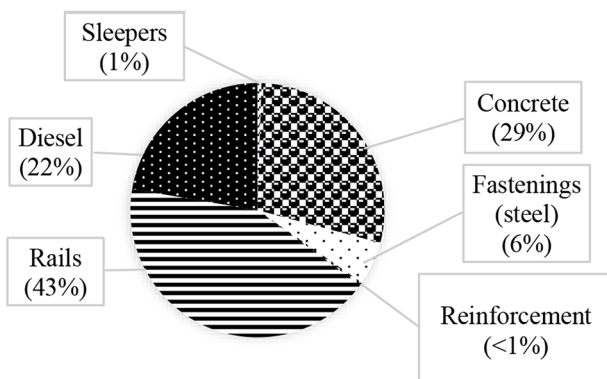


Fig. 7 Distribution of the life cycle CO₂e emission items for the ballastless track solution

largest emission source is manufacturing concrete for the track concrete layer (TCL) and the leveling layer. Another significant emission source is emissions generated by diesel consumption for transporting the tunnel rock material, which is the most significant diesel-consuming activity.

The study indicates that choosing a track with ballast is more detrimental to the climate from a life cycle perspective than choosing a track without ballast. It is also clear that the materials that make up the respective track form significantly contribute to the number of CO₂e emitted. The number of replacements for track components during the service life is also essential.

The natural modulus of elasticity of the tunnel floor is a significant factor in the design of the track forms, affecting the life cycle CO₂e emissions. For the ballastless track solution in the tunnel, the natural modulus of elasticity allows the structural modification of the ballastless track system Rheda 2000[®]. The structural modification implies optimization of the ballastless track system, resulting in the environmentally-friendly version called Rheda 2000[®]. This is achieved through (i) reducing the concrete content in

the track system and, thus, associated CO₂e emissions, (ii) using the cement CEM II with a lower content of clinker, contributing to a lower emission factor of the concrete, and (iii) eliminating the longitudinal reinforcement in TCL, and consequently reducing steel consumption and associated CO₂e emissions.

On the contrary, in the ballasted track solution, the modulus of elasticity of the tunnel floor contributes to an accelerated deterioration of the ballast. This increases the life cycle required for maintenance and associated CO₂e emissions.

4.2 Sensitivity analysis of the significant CO₂e emission factors

The current study identified several significant factors in the life cycle CO₂ equivalent emission. These factors are as follows.

- CO₂e emissions related to diesel consumption during.
 - transport of tunnel rock material.
 - track installation.
 - track maintenance and renewal.
- CO₂e emissions related to the manufacturing of.
 - rails.
 - sleepers.
 - concrete for TCL and the leveling layer.

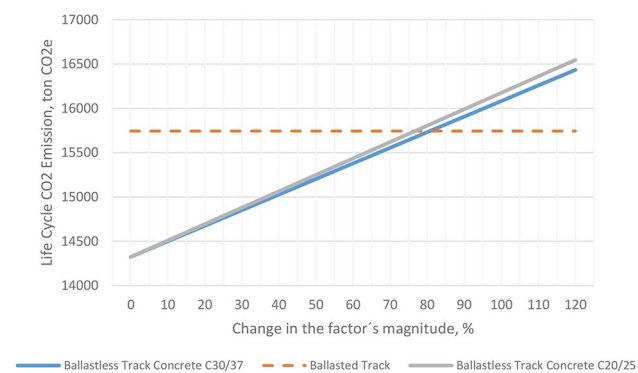
A sensitivity analysis was carried out to examine the influence rate of these factors on the life cycle CO₂e emission. Firstly, the consumption of diesel during corresponding track works has been estimated. Then, the magnitude of the significant factors with a rise of 10% was calculated. Further, the change in life cycle CO₂e emission for the track forms and the significant factors has been calculated using CICT. Finally, the difference between the change in life cycle CO₂e emission for the track forms. The outcome of these calculations is presented in Table 4.

The largest difference concerns the “Manufacturing of the concrete for TCL and the leveling layer.” The next largest difference is “Manufacturing of the sleepers.” The authors selected the first factor for further sensitivity analysis.

The calculation of the break-even point allows the determination of which value of the factor’s magnitude the ballastless track ceases to be more beneficial from the climate impact perspective than the ballasted track. The calculation for the factor “Manufacturing of the concrete for TCL and the leveling layer” encompasses the manufacturing of concrete of two types, i.e., C 30/37 for TCL and C20/25 for the leveling layer, the in-situ plain side concrete and

Table 4 Change in the life cycle of CO₂e emissions from the ballasted and the ballastless track solutions considering changes in the magnitude of the significant CO₂e emission factors by 10%

10% Change in CO ₂ e emission factor	Change in life cycle CO ₂ e emission, ton CO ₂ e		The difference in the life cycle CO ₂ e emission, ton CO ₂ e
	Ballasted Track	Ballastless Track	
Diesel consumption			
Consumption during transport of tunnel rock material, m ³	157	141	16
Consumption during track installation, m ³	43	36	7
Consumption during track maintenance and renewal, m ³	134	70	64
Manufacturing of the rails, sleepers, and concrete			
Rail manufacturing, m	603	611	-8
Manufacturing of the sleepers, pc	155	310	-155
Manufacturing of the concrete for TCL and the leveling layer, ton	0	244	-244

**Fig. 8** The break-even points for the factors “Manufacturing of the concrete C30/37” and “Manufacturing of the concrete C20/25” are shown

the in-situ plain filling concrete. The break-even point for each type of concrete was calculated for the given factor separately. The reason for this is the different environmental product declaration factors (EPD) for these two types of concrete. Implementing a rise of the factor’s magnitude by 10% at each stage, the simulation revealed that the original life cycle CO₂e emission of the ballastless track solution became equal to that of the ballasted track solution in the Hallsberg-Stenkumla tunnel (15 744-ton CO₂e) when the manufacturing of concrete C30/37 rises on 81%. For the factor “Manufacturing of the concrete C20/25” this value is 77%. Figure 8 displays the relationship between the change in the magnitude of the factors and the life cycle CO₂e emission of the ballastless track solution.

Based on experience, it can be assumed that the increase in the quantity of the concrete C30/37 for TCL by 81%, as well as the increase in the quantity of the concrete C20/25 for the leveling layer, the in-situ plain side concrete, and the in-situ plain filling concrete by 77% compared to that calculated in the study is technically infeasible. Consequently, when considering the factor of manufacturing the concrete, the authors of this study conclude that the life cycle CO₂e

emission of the ballastless track solution in the Hallsberg-Stenkumla tunnel cannot be higher than that of the ballasted track solution, thus confirming the robustness of the study outcome.

4.3 A look into the future

The calculations are made with the “worst-case” scenario, which means a lack of development in the production of fuels, vehicles, machines, or materials about climate performance and energy efficiency. The emission totals reported for each track form are likely overestimated.

With the CO₂e emission reduction targets agreed upon by the world countries in the Paris Agreement [15], intensive climate development work is underway with players using materials, fuels, and vehicles on which the Swedish Transport Administration depends in building facilities. In addition, the Swedish Transport Administration also sets specific climate requirements in its projects to encourage further development. The goal is to have Swedish Transport Administration contracts free of fossil fuels by 2030, and by 2040, the building and maintenance of the authority’s facilities will generate zero net CO₂e emissions. Machines that perform the work and materials used shall be embedded in the object. Exactly how much will be reduced and how quickly this adjustment will occur depends on how quickly production processes and the production of alternative fuels, vehicles, and machines can be adjusted. However, a plausible scenario is that a part of emissions from renewal occurring in the second half of the track asset life cycle can be eliminated.

5 Conclusions

This study investigated the effect of certain emission factors not adequately addressed in previous research. These factors are (i) the modulus of elasticity of track support,

which affects the design of track forms, (ii) differences in maintenance and renewal required for track forms in tunnel conditions, and (iii) recent developments to optimize the environmental impact of ballastless tracks.

The bottom-up approach [2], [11] developed for LCA has been applied to estimate the life cycle CO₂e emissions from the study case using CICT. It is found that for the ballasted track solution, the amount of renewal required for the track forms during its service life is the most critical factor influencing the life cycle CO₂e emissions; the amount of renewal has a more significant influence on life cycle CO₂e emissions than the CO₂e emissions associated with the embedded maintenance emission and component and material emissions. The influence of the modulus of elasticity of the tunnel bottom on the design, renewal, and maintenance of the geometrical quality of the track with ballast is essential. The most critical factors influencing CO₂e emissions in the design of a ballastless track system are the concrete and steel content and concrete type. The sensitivity analysis shows that changing this factor within a feasible range will not affect the study's outcome, i.e., the ballastless track form is preferable from a carbon emission perspective. For this track solution, the modulus of elasticity of the bottom of the tunnel has a decisive influence on modifying the ballastless track to reduce life cycle CO₂e emissions.

Among uncertainties, it is worth naming that proper design solutions for the ballastless track shall minimize the risk of frost damage in the drainage system. This lies beyond the scope of the current study and is one of the subjects of future investigation. Another important issue for future research scope is the investigation of the development of environmentally friendly materials, the manufacturing process for track components, and the use of climate-neutral machines to perform track works.

Acknowledgements The authors thank the Swedish Transport Administration for initiating and supporting this project. We also thank the managers and designers of PCM RailOne AG for their expertise and support in conducting the study.

Funding The Swedish Transport Administration, the R&D project 07830, funded the research work for this article. Open access funding provided by Lulea University of Technology.

Declarations

Conflict of interest The authors reported no potential conflict of interest.

Research involving human participants and/or animals This research did not involve any human participants and/or animals.

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