Embodied greenhouse gas assessment of railway infrastructure: the case of Austria

Matthias Landgraf1,∗ and Arpad Horvath2

1 Graz University of Technology, Rechbauerstrasse 12/II, Graz, Styria 8010, Austria
2 University of California, Berkeley, CA, United States of America
∗ Author to whom any correspondence should be addressed.

E-mail: m.landgraf@tugraz.at

Keywords: CO2, emissions, environmental impact, LCA, Austrian Federal Railways, railway infrastructure, railway track

Abstract
This study assesses life-cycle greenhouse gas (GHG) emissions associated with the entire railway infrastructure network of Austria, a first detailed study for a country, modelled through a top-down approach. Railway track is analysed for the first time in detail for a variety of specific boundary conditions using a bottom-up approach focusing on track renewal and maintenance. The methodology of standard elements allows for quantification of expected maintenance demands over the life cycle as well as determination of service life (SL). For this, the network is clustered into the main condition-affecting parameters, and documented maintenance and renewal measures are analysed and interpreted accordingly to estimate future behaviour. This Austrian approach used for assessing life-cycle costs serves as input for evaluating environmental impacts, a novel model. Data were gathered via environmental product declarations, governmental publications and company-specific environmental reports to correspond to the standard supply chains of the Austrian Federal Railways’ (ÖBB) life-cycle (manufacturing, construction, maintenance and reuse/recycling) infrastructure practices, and reflect actual transport distances, transport modes, the Austrian electricity mix and emissions. The railway infrastructure causes 235 000 tonnes of CO2eq emissions per year (0.3% of Austria’s total) based on the current infrastructure network, asset distribution and renewal rates. Within railway infrastructure, the track (including rails, fasteners, sleepers and ballast) is the main contributor to GHG emissions with 55% of the total. The GHG emissions associated with concrete tunnels are 16 times larger per kilometre per year than the railway track, but supply only 22% of the total emissions. The railway infrastructure contributes an additional 141% of GHG emissions over emissions from passenger traffic, which is much higher than previously anticipated. In-depth analysis of railway track shows that concrete sleepers with under-sleeper pads come with lower environmental impacts than conventional concrete sleepers. Higher traffic loads as well as narrow curves cause a significant increase in environmental impacts. For rails in a straight section with an SL of 50 years and two grinding measures, the costs regarding GHG emissions amount to €6500 per kilometre (including the production, construction and use phases) when calculating with a cost of €20 per tonne CO2eq on the market. Currently, this equals around 5% of the economic costs, but is expected to significantly increase as costs for environmental impacts are set to increase until 2050. Mitigation potential can be found in special rail steel production, reuse of materials, use of alternative fuels and efficient maintenance strategies.

1. Introduction

Mitigation of environmental impacts is one of the main challenges faced by society. Many global policies have been put in place to deal with the problem, including the Kyoto Protocol [1], the Paris Agreement [2, 3] and the Montreal Protocol [4]. Within the European Union, the European Trading System (ETS) was established in
2005 as the world’s first carbon market [5, 6]. Within the context of the Paris Agreement, the European Green
Deal was established in 2019 with the overarching aim of making Europe climate neutral by 2050 [7–9]. In
Austria, the policy relating to transport and infrastructure has the title #mission2030 [10]. The aim is to reduce
greenhouse gas (GHG) emissions within the mobility sector by 50% before 2050. Rail transport is already a
GHG-efficient mode. Figure 1 shows a comparison of different transport modes in Austria based on their
direct GHG emissions per passenger kilometre travelled (PKT) due to operation. Most studies and regulations
for this issue have focused on combusted fuel and electric power consumption based on direct and indirect
emissions.

In the past, the regulatory focus has widely been on tailpipe emissions only, neglecting the environmental
impacts of manufacturing, construction, maintenance and disposal of infrastructure components and also of
vehicles [12]. Recently, several standards and working documents have been published on a European scale.
The standards ÖNORM EN 14040 [13] and 14044 [14] as well as guidance document ONR CEN ISO/TS 14071
[15] specifically focus on life-cycle assessment (LCA) and cover all phases of the life cycle. The methodology
and principles of establishing environmental product declarations (EPDs), which are used as input data within
this study, are regulated within ÖNORM EN 15804 [16].

This paper describes a comprehensive approach to assessing GHG emissions associated with the Austrian
rail network infrastructure (including communications, geotechnics, noise barriers, power supply, signalling,
structures, track and tunnels). The main drivers are analysed and discussed in detail. The approach chosen
to cover all relevant information about the life cycle of railway infrastructure is the use of so-called stan-
dard elements, containing the expected service life (SL) of an asset and information on necessary maintenance
measures throughout the life cycle for specific boundary conditions. The aim is to use this cost-based knowl-
edge modelling approach as part of the LCA of railway infrastructure. This enables analysis to be made of
the main drivers of environmental impact in the railway infrastructure in order to show potential for mitigation.
Moreover, a comparison of the impacts per PKT in rail transport shows the need to include infrastructure
within these considerations. This approach can be used in other countries as well, with consideration of local
boundary conditions, railway design and engineering, supply chains, energy sources and emissions.

LCA is the standard environmental method used to understand, document and compare how a product
or service is provided from cradle to grave [17]. A growing body of literature highlights the need to under-
stand the embodied GHG emissions of transport infrastructure provision. In 2007, studies in the United States
[18, 19] showed that total life-cycle emissions of freight transportation modes are underestimated if only
tailpipe emissions are accounted for. Chester and Horvath [12] compared standard (heavy) rail as well as urban
light rail systems with other transportation modes, followed up by studies in 2010 and 2012 [20, 21] which
determined the life-cycle environmental performance of the California high speed rail (CAHSR) compared
with alternative transport modes in scenarios of different occupancy rates and evolving technologies. The
CAHSR was found to have lower end-use energy consumption and GHG emissions at high occupancy and
higher SO2 emissions at low occupancy as rail vehicles are mainly powered by fossil-based electricity. Assess-
ment of the life-cycle energy usage and carbon emission efficiency of high-speed rail (HSR) showed that the
CAHSR is predicted to be more environmentally efficient than the Florida HSR due to higher ridership predi-
ctions [22]. Ridership predictions are crucial parts of any comprehensive LCA. Results for specific corridors

---

Figure 1. GHG emissions of different transport modes for Austrian boundary conditions according to [11].
in Spain show that construction of HSR lines is not justified in terms of energy savings and emission reductions due to the low passenger demand [23, 24]. Also, assessments in Germany comparing GHG emissions for various cases concluded that emissions both per track kilometre and per PKT are up to 3.5 times higher for building HSR lines than standard lines within the network of Deutsche Bahn [25]. In-depth research including Monte Carlo simulation to deal with uncertainties in future transport demands, technology and power production found that traffic volumes of more than 10 million annual one-way trips are usually required to balance the annualized emissions from HSR construction [26]. A Swedish study [27] used LCA to research the mitigating climate change effects of a proposed Swedish HSR track and found significant reduction in GHG emissions because of the shift of transportation modes to HSR. However, new railway construction, upgrading existing lines to HSR operation and maintenance may weaken the benefits. A study using data from 285 prefecture-level cities in China between 2003 and 2013 showed that HSR reduces environmental pollution by 7.35% [28].

Any comparisons of environmental impacts including train operation, vehicles and infrastructure are heavily dependent on the energy supply for train operation [29]. Since most studies mentioned focus on newly built electrified HSR the main influencing parameter is the regional electricity mix. The share of GHG emissions within the railway system associated with train operation is 58% in Turkey’s HSR system (69% in conventional railway operations) [30] and 69% on Portugal’s HSR lines [31]. The environmental impacts of HSR in China are also dominated by train operation in most impact categories [32], as is the case for HSR in Germany (Hannover–Wuerzburg) regarding accumulated energy demand [33]. An analysis of air emissions associated with the transportation of goods by road, rail and air in the United States showed that the vehicle use phase is responsible for approximately 70% of total emissions of CO₂ for all three modes [34]. In general, rail transport is often, but not always, environmentally preferable to truck transport [35]. Based on the Belgian electricity supply mix, a shift from diesel trains to electric trains would lead to a 26% reduction in the environmental impact on climate change [36].

Specifically focusing on railway infrastructure, a process-based LCA study on GHG emissions estimation in the construction of the CAHSR infrastructure with specification of several infrastructure types depending on terrain was performed by Chang and Kendall [37]. It found that 80% of the infrastructure emissions resulted from material production and that tunnelling and aerial structures—which comprised only 15% of the route length—resulted in 60% of the emissions. Also, research on the HSR in China between Beijing and Tianjin states that upstream material production has the dominant effects, accounting for over 89% of the carbon, water, land and material footprints [38]. Major contributions to environmental impact stem from rails, roadbed and civil engineering structures [39]. The main GHG emissions source for HSR track construction is the production of steel for the rails (about 50% of the total result) [40]. Based on Norwegian boundary conditions, construction of a single-track line with passing loops would reduce the total environmental impact by around 25% compared with a double-track line [41]. In Sweden, an in-depth analysis of the Bothnia line [42] led to the publication of several EPDs for various parts of the railway infrastructure. A holistic approach for estimating carbon emissions of road and rail transportation was used to evaluate the Greek intercity network [43]. It concluded that railway infrastructure construction causes more emissions than road infrastructure, which is counterbalanced by environmentally friendly rail operation. Sasidharan et al [44] executed a whole life cycle approach comparing a number of different maintenance strategies based on existing degradation models. This approach combines life cycle costs (construction, operation, maintenance, end of life), non-construction costs, income and externalities (transport-related NOₓ, SO₂ and CO₂ emissions). The study was applied to three different route types on the UK main-line railway network and concluded that the do-minimum maintenance strategy is not the most beneficial strategy when considering whole life-cycle costs. A novel approach was conducted by Lederer et al [45], exploring the anthropogenic resources deposited in Vienna’s subway network. Results show that 3% of built-in materials can be seen as potentially extractable resources for secondary raw materials.

The most comprehensive review of embodied emissions in rail infrastructure was conducted by Olugbenga et al [46], covering a full-paper review of 100 articles, considering whether embodied impacts are considered and real-world data are applied, and the level of detail within LCA calculation and research goals. The embodied emissions associated with the case studies range from 0.5 to 12 700 tCO₂ km⁻¹; much of the variation is dependent on the proportion of the rail line at-grade, elevated or in a tunnel. The statistical model finds that overall ∼941 (±168) tCO₂eq are embodied per kilometre of rail at-grade, and tunnelling results in 27 (±5) times more embodied GHG per kilometre than at-grade construction.

Chester and Ryerson [47] point out the grand challenges of environmental assessments of future long-distance travel, including the spatial incompatibility between HSR and other long-distance modes that is often ignored, an environmental review process that obviates modal alternatives, siloed interest in particular environmental impacts, a dearth of data on future vehicle and energy sources and a poor understanding of secondary impacts, particularly on land use. There have been numerous studies on land use—transport
Table 1. Goal and scope of the study.

| Methodology      | Scope                                                                 | Goal                      | Functional unit                      |
|------------------|----------------------------------------------------------------------|---------------------------|--------------------------------------|
| Top-down approach| Assess environmental impacts of relevant assets within the Austrian railway infrastructure network | Identify the main driver on a network-wide basis | Energy demand and GHG emissions per year within the Austrian network |
| Bottom-up approach| Assess GHG emissions of railway track renewal as the main network-wide driver of environmental impacts within railway infrastructure in Austria. This includes specific supply chains, production, construction, and operation of railway track under various boundary conditions | Identify the most environmentally friendly choice of components for railway track | GHG emissions per kilometre track and year |

connections. In 1996, Newman and Kenworthy [48] analysed this connection in a historical context as well as patterns in different cities at that time, discussing the problems of unconnected automobile cities in various case studies. A comprehensive review of empirical studies has found that, compared with road infrastructure, the impact of rail infrastructure is often less significant for land cover or population and employment density change [49]. In the future, the adoption of new modelling approaches to better represent rapid social and technological change and to concurrently assess the resilience and sustainability implications of different land-use and transport policies will be crucial [50].

All these studies have focused on railways in themselves and comparison with other transport modes. Specificity to local conditions and representativeness for the entire railway network have been missing from most of the published studies. Railway track is most often represented with a generic SL neglecting a variation in maintenance demands and service lives due to different boundary conditions such as alignment, types of components and traffic load. Also, generic assumptions for various materials and their origins are made and generic, average emission factors are used, often from other countries and time periods. The use of non-specific data is a major source of uncertainties about the usefulness of these studies for making environmental improvements and promoting policy changes.

We present the first LCA of the railway network of Austria; in fact, the first comprehensive assessment of a country’s railway infrastructure, using a two-pronged approach (table 1), focusing only on GHG emissions due to current data availability. First, a top-down approach analyses the environmental impacts of infrastructure assets within the entire network using energy and GHG emissions per year within the Austrian network as a functional unit. We show that railway track, as the main contributor to GHG emissions, is thus worthy of detailed analysis. Then a bottom-up approach with in-depth knowledge regarding supply chains and materials assesses railway track renewal in order to identify potentials for mitigation of environmental impacts. Moreover, the method of standard elements allows for the comparison of different scenarios regarding component composition of track superstructure and its resultant SL. This shows that the right choice of superstructure component composition can mitigate environmental impacts. This analysis is executed for various boundary conditions using GHG emissions per kilometre of track and year as the functional unit in order to compare scenarios with varying SLs.

2. Methods

A prerequisite for any LC consideration is knowledge about the behaviour of an asset or product. This should include knowledge about the maintenance demands and the SL. The Institute of Railway Engineering and Transport Economy of Graz University of Technology operates a data warehouse for research purposes including all track asset, maintenance and measurement data for the Austrian Federal Railways (ÖBB). Thus, the type, age and distribution of infrastructure assets as well as specific construction machinery used for renewal or maintenance measures can be extracted.

2.1. Methodology of standard elements

In close cooperation with ÖBB, the Institute for Railway Engineering and Transport Economy at Graz University of Technology developed a life-cycle cost (LCC) model based on standard elements [51], which clusters the relevant boundary conditions within a network based on comparable degradation behaviour. Hence, these clusters (standard elements) show similar maintenance demands and service lives.
Table 2. Standard elements of railway track.

| Line description | Radial class |
|------------------|--------------|
| Gross tons per day/track | Rail profile | Steel grade | Sleeper |
| [traffic load class] | [profile] | [grade] | [type] |
| Maintenance | Service life in years | X | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | — |

Track construction 1

Ballast cleaning No. in SL

Tamping No. in SL 1 1

Grinding No. in SL 1

Rail exchange No. in SL — —

Generally, track behaviour over time is mainly influenced by superstructure configuration (sleeper type, rail profile, steel grade), traffic load and the occurrence and radii of curved sections. The variation in these characteristics results in different service lives and maintenance demands. This leads to significant variations in life cycles, or rather LCCs, for the various sections. Within this approach, maintenance cycles and SLs for infrastructure assets are determined based on a twofold methodology: on the one hand we rely on analytics of measurement data dating back to 2002 assessing the maintenance cycles and service lives for specific boundary conditions [52–56]; on the other hand we can fill any data gaps using experience, documented maintenance works and knowledge from regional track engineers.

Railway track defined by specific boundary conditions and parameters is referred to as a standard element (table 2). This standard element shows which maintenance task (e.g., grinding, tamping) is to be expected in a specific year within the SL. This working cycle is available over the SL and includes the maintenance tasks and the SL to be expected under specific boundary conditions. These boundary conditions are defined by the parameters radius class (e.g., <250 m, 250–400 m, 400–600 m), gross tonnes (gt) per day and track as reflecting traffic load, rail profile (e.g., UIC 60E1, UIC 54E2), steel grade (e.g., R 260, 350 HT) and sleeper type (e.g., concrete, wooden).

Hence, the underlying working cycle together with the SL represent the expected behaviour under the specific boundary conditions. As these standard elements have been established for all relevant combinations of specific boundary conditions, we can describe the maintenance cycles and SL of the entire Austrian rail network. This in turn enables any kind of evaluation on a strategic level, such as estimating maintenance and renewal demands, for decades to come. Moreover, this model makes it possible to identify the component composition showing the lowest LCC within a specific set of boundary conditions. Standard elements represent expected maintenance and SL based on a net-wide average for specific boundary conditions. Thus, it allows for the prediction of network-wise renewal and maintenance budgets as well as providing viable input for strategic network-wide analyses such as this one. However, it is not possible to predict maintenance works for specific cross-sections. These in-depth technical evaluations require section-specific time-series analyses of measurement values [57, 58]. This information is already available, but not for all relevant maintenance tasks or on a network-wide basis.

Open track and switches are crucial matters of expense for railway infrastructure. The LCCs of railway track are mainly defined by depreciation, maintenance and the costs of operational hindrances quantifying non-availability of track [51]. Besides quantifying LCC, this methodology of standard elements for specific boundary conditions is a perfect basis for LCA since we already have knowledge about maintenance demands and the SL of railway track under specific boundary conditions. Hence, the challenge lies in the calculation of the environmental impacts based on that input. This calculation is executed within a two-pronged process: first, as a top-down approach for the entire infrastructure network including all linear assets as well as station buildings, and second, as an in-depth, bottom-up approach for railway track.

2.2. Top-down approach for railway infrastructure network

Modelling the Austrian network is carried out using a top-down approach in which EPDs [59–64] as well as published calculations regarding the impacts of various railway infrastructure assets from the International Union of Railways (UIC) [65] and Tuchscheidt et al [66] are used as sources of emission factors that can
be applied to materials and equipment use to estimate emissions. These emission factors are then applied to specific lengths and numbers of assets within the Austrian network.

Railway infrastructure managers own a variety of different assets, which provide the foundation for safe and efficient rail transport. These assets range from the supply of traction power to the railway tracks of the network. ÖBB owns 6817 km of track [67] and various assets consisting of different materials and boundary conditions. Of those, 5564 km are classified as main lines and the rest as regional, supplementary or branch lines. Figure 2 shows the characteristics and shape of the Austrian railway network. The displayed main and regional lines are owned and operated by Austrian Federal Railways (ÖBB) and are included in this study. The Austrian railway network represents mixed traffic operations. Daily operated trains are 74% local, 20% freight and 6% long-distance [68].

The assets, their various lengths and service lives as input for the LCA are shown in the supplementary information (https://stacks.iop.org/ERIS/1/025008/mmedia).

The fundamental environmental factors used to determine a component’s energy and emissions come from a variety of sources. We focused on finding EPDs [70] for specific materials. EPDs represent a voluntary third-party certification that refers to realistic information about the environmental performances of products. In recent years, European companies have increasingly published EPDs. The Scandinavian region in particular is playing a pioneering role in this development, which is strongly linked to public clients implementing environmental aspects within their procurement processes [71]. The underlying sources for environmental factors and their area of usage in this paper are listed in Table 3. The table comprises the major material composition of the various assets (a few small-mass materials are not included).

2.3. Bottom-up approach for railway track
A detailed bottom-up approach is carried out for renewal of ballasted railway track, reflecting specific Austrian boundary conditions and supply chains. Since previous studies mainly focused on greenfield HSR projects, this is the first in-depth study to focus on embodied emissions of track renewal and maintenance including the influence of different boundary conditions within a railway network. In Austria, the main focus is on maintaining and renewing the existing network, leading to an average annual renewal of 197.4 km of track between 2014 and 2018 [67]. Since 2008, Austrian Federal Railways inaugurated 170 km [68] of new stretches in operation, resulting in an average of 13 km of newly built lines per year. Thus, the amount of track renewal is higher than that of newly built track construction by a factor of 15. This results in an annual quota of 2.9% of renewal demand within the railway network. In a European context, this leads to an annual track renewal demand of 11 225 km [99].

The methodology of standard elements allows an in-depth representation of specific boundary conditions to be made and also underlying degradation models of railway track leading to the establishment of corresponding maintenance cycles and SLs. These calculations are carried out for different types of sleepers, various traffic loads and curvatures since these two boundary conditions are the main influence on track degradation and consequently maintenance demands and SL [55, 100]. This leads to significant variations in environmental impacts. The three common sleeper types used in Austria are wooden sleepers, concrete sleepers and concrete.
### Table 3. Input data for materials and processes.

| Materials/processes                  | Use  | Source |
|--------------------------------------|------|--------|
| Aluminium                            | Tr, C | [72]   |
| Asphalt, 6% bitumen                  | B    | EPD [73] |
| Beech wood                           | Tr   | [74]   |
| Bitumen                              | B    | [75]   |
| Portland cement CEM I                | Tu   | EPD [76] |
| Portland cement CEM II               | Tr   | EPD [77] |
| Concrete for pre-cast elements       | Tr, Tu, A, C, B | EPD [78] |
| Construction machinery               | Tr, Tu, A, B | [11, 80] |
| Copper                               | C    | [81]   |
| Creosote WEI type C                  | Tr   | [82]   |
| Deforestation wood                   | Tr, A | [83] |
| Energy consumption                   | Tr, Tu, A, C, B | [84] |
| Explosive Tovex                      | Tr, Tu | EPD [85] |
| Fibreoptic cable                     | C    | EPD [86] |
| Galvanized steel                     | Tr, Tu, A, C | EPD [87] |
| Geotextile                           | Tr, Tu, C | EPD [88] |
| Glass wool                           | C    | [72]   |
| Glued wood                           | A, C, B | EPD [89] |
| Gravel                               | Tr   | [90]   |
| Hardened glass                       | A    | [72]   |
| Insulation board                     | Tu   | EPD [91] |
| Lead                                 | C    | [72]   |
| Lime                                 | Tu   | [92]   |
| Polyethylene HDPE, LDPE              | Tr, Tu, C | [93] |
| Rail steel                           | Tr   | EPD [94] |
| Rail pads, under sleeper pads        | Tr   | SR [95] |
| Rebar steel                          | Tr, Tu, A, C, B | EPD [96] |
| Stainless steel                      | Tu   | [97]   |
| Steel general, AT                    | Tu, A, B | SR [98] |
| Styrene for production of insulators | C    | [90]   |
| Tank coating                         | C    | [90]   |
| Transports                           | Tr, Tu, A, C, B | [11] |

*Tr, Tram; C, Communication; EPD, environmental product declaration; SR, sustainability report; T, tunnel.*

### Table 4. Maintenance demands in the life cycle and service life for tracks with 30 000–45 000 gt day\(^{-1}\), straight section, rail steel grade R 260.

| Maintenance demands in the life cycle | Service life |
|--------------------------------------|--------------|
| Wooden sleepers,                     | Tamping 6×   | 35 years |
| Rail profile 54E2                    | Grinding 1×  |            |
| Concrete sleepers,                   | Tamping 6×   | 36 years |
| Rail profile 60E1                    | Grinding 1×  |            |
| Concrete sleepers with under sleeper pads, | Tamping 4× | 50 years |
| Rail profile 60E1                    | Grinding 2×  |            |

sleepers with under-sleeper pads. In order to compare the GHG emissions of these different types of sleepers, we chose the line-specific boundary conditions of a moderate traffic load of 30 000–45 000 gt day\(^{-1}\) and track (this is equal to an average of 13.7 million gt year\(^{-1}\)) in a straight section, which is defined as having a radius greater than 3000 m (table 4). For this specific parameter set, both wooden and concrete sleeper-equipped tracks demand six tamping and one grinding measure within an SL of 35 years (wood) and 36 years (concrete), respectively. Concrete sleepers with under-sleeper pads combine the mechanical effects of conventional concrete sleepers (long-lasting and non-weathering material) and wooden sleepers (homogeneous vertical load distribution due to elasticity of the material). They preserve railway ballast and significantly improve track quality behaviour [101, 102] as load distribution is enhanced and sleeper voids [103] are prevented. This leads to an SL of 50 years, requiring four tamping and two grinding measures.

Track construction and maintenance include the transport of machinery, the track work itself and the materials used. In Austria, track construction is carried out with track-bound and continuously operational
machinery. GHG emissions for track work are calculated using

\[ GHG_a = rel_{non-el} \times \left( n_t \times l_t \times \frac{1}{l_{ws,a}} \times df \right) \times EF_{non-el} + rel_{el} \times \left( n_t \times l_t \times \frac{1}{l_{ws,a}} \times df \right) \times EF_{el} + \frac{p_{a}}{f_{ca}} \times EF_{Diesel} \]

where \( GHG_a \) (in units of kg CO₂eq) denotes emissions of track work, \( rel_{el} \) and \( rel_{non-el} \) are the proportion of transportation of track-work machinery to and from a construction site with electric- and diesel-powered locomotives as well as their applicable emission factors \( EF_{el} \) and \( EF_{non-el} \) (in kg CO₂eq km⁻¹), \( n_t \) is the number of necessary transportation processes with length \( l_t \) (in km), \( l_{ws,a} \) is the average performance length of track-work machinery within a work shift (in km) and \( df \) is the decreasing factor of the usual transportation length of track-work machinery due to intelligent construction site scheduling. The productivity per hour is represented by \( p_{a} \) (in km h⁻¹) and the corresponding fuel consumption is \( f_{ca} \) (in l h⁻¹).

Track construction is carried out with a track-relaying machine burning 131.54 l of diesel per hour [80]. Taking the transport of machinery and a productivity of 200 m h⁻¹ into account, this equals 2281 kg CO₂eq km⁻¹ for re-laying of railway track superstructure. Emissions of track work regarding ballast cleaning (performance 83 m h⁻¹), tamping (625 m h⁻¹), grinding (412 m h⁻¹) and rail exchange (714 m h⁻¹) are also calculated according to equation (1). Based on field data collected in the United States, tamping machines were found to process 4.25 m of track per litre of diesel fuel [104]. This is similar to the calculation for tamping in this study (3.96 m of track per litre of diesel, using a newer generation of tamping machinery). In addition, rail pad exchange is included. As this mainly involves manual labour, the GHG emissions include the production and transport of materials.

Possibilities of reusing, reprocessing and recycling within the railway infrastructure have been included as currently executed by ÖBB, whereas further potential for circular economy remains subject to research. ÖBB can reuse about 20% of rails and 15% of concrete sleepers after completion of the first life cycle, mostly on tracks with less traffic. In both cases, the SL can be doubled as a result of reuse. In the case of ballast, there is high potential for reuse as cleaning is carried out at the end of the life cycle. An average of 40% of ballast can be reused due to on-site ballast cleaning. The amount of scrap steel within the production process of rails has been considered.

3. Results

3.1. Whole infrastructure approach
Carrying out the top-down approach for the whole railway infrastructure shows that track is the main contributor of GHG emissions and energy demand within the Austrian network (figure 3). This calculation considers
manufacturing, construction and associated freight transports as well as the SLs of the specific assets, as defined within the attached supplementary information. There is high potential for innovation regarding environmental issues as in Austria there is a continuous renewal rate of around 3% of the length of the track network each year. This means that any innovation can be implemented promptly whereas construction of long tunnels is executed less frequently. As already pointed out in previous studies [37], tunnels and aerial structures cause the highest emissions per kilometre within the Austrian network. For Austrian conditions, GHG emissions per kilometre and year of concrete tunnels are 16 times higher than for railway track.

The sum of cradle-to-gate emissions per year (based on the current infrastructure network, asset distribution and renewal rates) of railway infrastructure amounts to 234,730 tonnes CO₂eq. In 2018, ÖBB processed 11.5 billion PKT, equal to the operation of 5,449 trains per day [68]. The GHG emission factor for rail passenger transport in the same year was 14.4 g CO₂eq per PKT as 85.8% of passenger trains are operated using a catenary system [11]. Therefore, 165,600 tonnes CO₂eq year⁻¹ are caused by passenger operations. Thus, for Austrian boundary conditions, railway infrastructure contributes an additional 141% of GHG emissions over emissions associated with passenger operations. This number and conclusion deviates from previous studies [30, 31], which suggest that the majority of environmental impacts are caused by train operation. The Austrian Federal Railways use electricity for traction power from renewable sources only (95% hydropower, 5% other renewable energy sources) [68], which is rare among rail operators. Apart from the regional electricity mix, there are various other factors influencing GHG emissions from train operations. The use of alternative propulsion systems will increasingly replace diesel-powered trains wherever electrification is not feasible. Trains powered by batteries, hydrogen, synthetic fuels or biofuels will be used in passenger transport on regional lines, freight transport, shunting areas and for track work machinery [105]. In addition to improving the environmental efficiency of railway infrastructure or train operation, we must not neglect the strong links within the railway system. Optimization of operational capacity and train energy efficiency often requires infrastructural expansion. On the one hand, intensive measures such as additional tracks, realignment, elimination of level crossings, building tunnels instead of mountainous lines or restructuring of stations (e.g., expanding terminals into throughway stations) may lead to higher capacity and lower energy use. On the other hand, comparably small infrastructural changes can lead to essential decreases in train energy demand as well. This can be achieved by adapting the signalling system (shortening block lengths or aiming for a moving block system) and evolving towards sophisticated traffic management systems [106] and automated train operation [107]. Algorithm-based optimization of train trajectories may reduce the total energy consumption by 7% to 8% on high-speed main lines [108, 109] and by up to 14.5% on metro lines [109].

### 3.2. In-depth modelling of railway track

An in-depth bottom-up approach is carried out for the main contributor of GHG emissions within the Austrian railway network, ballasted railway track. The analyses compare various sleeper types, traffic densities and curves on routes.

Wooden sleepers show the highest GHG emissions per km of track and year (figure 4). As they reach a comparable SL to concrete sleepers with identical maintenance demands within the life cycle, this is mainly caused by sleeper manufacture and a lower potential for reuse than with concrete sleepers. The lowest GHG emissions per km of track and year result for concrete sleepers with under-sleeper pads. The material of under-sleeper pads causes higher emissions within the production process, which can easily be balanced out due to the significantly higher SL compared with conventional concrete sleepers. For this specific set of boundary
conditions, an SL extension of 3.21 years compensates for the additional emissions in the manufacturing process. Under-sleeper pads, rail pads, fasteners, sleeper material and reinforcement steel with concrete sleepers are all summed up as ‘sleeper’.

For the boundary conditions shown in figure 4, rails and sleepers are the main drivers of environmental impacts whereas maintenance and construction account for 12% on average. This includes track work as well as materials such as additional ballast for tamping measures. If rail exchange is necessary, rail material is also included. Hence there is high potential for mitigation in maintenance strategies and alternative drives for maintenance and construction equipment. The total environmental impacts of manufacturing, construction and operation of the three types of superstructure amount to 442 to 474 tCO₂eq per km of track. Embodied emissions associated with the analysed case studies by Olugbenga et al. [46] range from 0.5 to 12 700 tCO₂eq km⁻¹; the statistical model finds that overall ~941 (± 168) tCO₂eq are embodied per kilometre of rail at-grade. Thus, the calculated values in this study are at the lower end. This is due to the fact that the analysed case studies are based on HSR greenfield construction. The present study focuses on mixed-traffic track renewal, which means that substructure construction is not necessary, and ballast can partly be reused by executing track-bound ballast cleaning.

Traffic density means a significant change for railway track behaviour as the impact of load influences track degradation: higher traffic loads equal higher maintenance demands and a shorter SL of track. For example, wooden sleepers with a traffic load cluster of >70 000 gt day⁻¹ and track (>25.6 million gt day⁻¹ and track) have an SL of 26 years and ten necessary tamping measures, whereas the lowest traffic density cluster...
(15000–30000 gt day$^{-1}$ and track) shows an SL of 35 years with only five tamping measures. These effects directly correspond to the environmental impacts of infrastructure (figure 5). The same is true for concrete sleepers and concrete sleepers with under-sleeper pads. The ranking within the three types of superstructures is not affected.

Another significant parameter influencing track degradation is curvature of the routes. In Austria, where there is a significant proportion of mountainous lines, this impact must be considered. The SL of track is reduced in tight curves, while the maintenance demand increases significantly. For radii of 250 m and less, the standard type of superstructure is wooden sleepers. Due to vertical forces induced by traffic load, the SL is only 25 years with the following essential maintenance measures: tamping ten times, rail grinding eight times and rail exchange 3.5 times (0.5 means that only the outer rail has to be exchanged as wear predominantly occurs on the outer rails). In this context, figure 6 shows a slight increase in environmental impacts from straight sections ($R > 3000$ m) to sections with a radius of 400 m up to 600 m. After that, however, there is an exponential increase in environmental impacts. The standard steel grade is R 260, whereas in sections with radii of 600 m and less we include R 350 HT for our calculations. The higher steel grade in combination with the head hardening production process of this rail steel type counteracts increasing lateral forces in tight curves and thus decreases maintenance demands for these boundary conditions.

These results show that environmental impacts of railway track are the main contributor within railway infrastructure and that they can vary significantly for different boundary conditions of railway track. Thus, these boundary conditions must be included in any detailed assessment of railway track. Due to the in-depth knowledge of track behaviour over time for different boundary conditions, this was executed in this study.

### 3.3. Analyses of uncertainties

Assessment of the environmental performance of infrastructure depends greatly on reliable input data. In this study we focus on publicly available data in order to allocate material masses and estimate their GHG emissions. Some materials provide a variety of different regional EPDs showing a variance in emission factors. In the context of the building construction sector, Passer et al [110] conducted a critical review of EPDs in different European countries. They found that harmonization is needed on the impact categories and assessment models or indicators, on the system boundaries and SL of products and buildings, on the definition of scenarios (transport, use phase and end of life), allocation rules, biogenic carbon emissions, end-of-life approach and data quality requirements. European EPD programmes are based on EN 15804 [16]; however, only a limited number of scientific papers have evaluated the influence of the use of different generic databases, which can result in different results on the EPD level. These uncertainties are also true for the present study, as Olugbenga et al [46] also pointed out when they reviewed 100 case studies of LCAs in the railway sector.

Regarding the in-depth bottom-up modelling of railway track, we were able to show that rails and sleepers are the main contributors to the GHG balance of railway track. Input data for rail steel, concrete, rebar steel and beech wood come from reliable, updated and regionally specific sources. Moreover, production processes are directly connected to the railway track industry and not adopted from other industries. This means that the main railway track materials show a minimum of uncertainties. This is also valid for data in the context of track work and maintenance, as average fuel consumption is based on mean values from actual construction sites in Austria.

However, SL is a main influencing parameter which is why it needs to be addressed in detail. As already mentioned, we can compare different boundary conditions of railway track due to the information within standard elements. This methodology includes an expected SL based on the average behaviour of set boundary conditions. Within the database of Graz University of Technology, the expected SL of every section is assigned based on its boundary conditions within the entire network. In case of renewal of a track section, we can compare the actual SL reached with that expected according to standard elements. These data can be used for validating the standard elements.

For calculating distribution functions in order to quantify uncertainties within this LCA, reinvestment projects of Austrian Federal Railways from the years 2007 to 2019 were examined. These examinations comprise 407 km of track renewal with concrete sleepers and 675 km with wooden sleepers. For wooden sleepers, SLs at the time of reinvestment show a Laplace distribution ($\mu = 1$, $b = 7.744$) with a mean deviation of 1 year. This means that values for expected SL according to standard elements show a high accuracy with regard to average values. However, this Laplace distribution shows a standard deviation of $-1.25$ and $3.2$ years for a probability density of 0.05 (25th percentile). For concrete sleepers, the normal distribution ($\mu = -0.567$, $\sigma = 12.863$) is the best fit with a mean value even under 1 year. Standard deviations at a probability density of 0.03 (25th percentile) are $-4.6$ and $3.5$ years, respectively. Concrete sleepers with under-sleeper pads show lower standard deviations but very limited sample sizes since they were installed for the first time relatively recently, in 1992. Concrete sleepers with under-sleeper pads show a lower degradation rate than concrete sleepers.
sleepers without under-sleeper pads, but very similar degradation characteristics [102]. Thus, the normal distribution is set for concrete sleepers with under-sleeper pads.

Figure 7 shows the GHG emissions of straight track sections of railway track with wooden or concrete sleepers and concrete under-sleeper pads, including uncertainties about SL. It shows that concrete under-sleeper pads in any case show the lowest GHG emissions per km and year. However, the results for wooden and concrete sleepers may change due to a variation in the SL of track.

4. Conclusion and outlook

SL is one of the main parameters influencing the environmental impacts of railway infrastructure. Hence initial quality and a proper maintenance strategy are key to mitigation of GHG emissions. Railway track (55% within the Austrian network), and especially rails (54% within railway track), are the main drivers of environmental impacts within railway infrastructure networks. Hence, reducing emissions from steel production is one major potential mitigation, not only in railways but also in many other industries. In Austria, steel is produced using the basic oxygen furnace (BOF) process. This guarantees high quality, leading to a long SL for rails, but is emission intensive. The electric arc furnace (EAF) process uses ferrous scrap which is melted using electric energy. An in-depth analysis comparing both processes based on Polish steel production sites [111] showed that EAF steel requires only 23% of the energy of BOF steel. Also, embracing the circular economy principle within railway track infrastructure can essentially contribute to mitigation of environmental impacts. Several studies [112–114] have analysed the behaviour of steel slag used as ballast material, which would mitigate the need for disposal of steel slag and simultaneously save scarce resources. Ferdous et al [115] conducted a literature review on recent developments, challenges and future prospects of composite railway sleepers, which would also allow for the use of recycled materials instead of concrete or wooden sleepers.

Depending on the specific electricity mix, this can lead to a significant potential for mitigating GHG emissions in the railway system. As track work in construction and maintenance is mainly executed with heavy equipment combusting diesel, a switch to alternative drives (most notably electric) could have a significant impact on the GHG emissions of railway track. Track work currently contributes about 12% of railway track GHG emissions.

The presented calculations include cradle-to-gate emissions, maintenance (including materials), SLs for the different boundary conditions and reuse and recycling within the railway system. Possible scenarios regarding disposal and downgrading of products as well as carbon capture and storage have not been included. The conducted bottom-up analysis is based on country-specific supply chains and production processes. Since track renewal is a process-oriented and—in Austria—a track-bound construction activity, these analyses not only cover specific sections within the network but also general renewal construction in Austria. As mentioned, the amount of track renewal in Austria is roughly 200 km year⁻¹ and at a European level more than 11 000 km year⁻¹.

From a policy point of view, the goal should be to automatically calculate GHG emissions within the procurement process and include the relevant environmental costs. Hence rising costs of emissions allowances (in a cap-and-trade system) lead directly to higher prices in the procurement process and should compel contractors and manufacturers to invest in low-emission products. For rails in a straight section with a SL of 50 years and two grinding measures, the costs of GHG emissions amount to €6500 per kilometre (including the...
production, construction and use phases) when calculating with a cost of €20 per tonne CO2eq on the market. Currently, this equals around 5% of the comparable economic costs, but this is expected to significantly increase because costs for environmental impacts are set to increase until 2050 [116].

Acknowledgments

The Institute of Railway Engineering and Transport Economy of Graz University of Technology operates a data warehouse including asset data, measurement data and documentary records of ÖBB track works. Thanks to this close cooperation, the methodology of standard elements and in-depth knowledge about track degradation, together with the parameters of track works, could be established. This information served as viable input data for the present study. We would also like to thank the reviewers for providing feedback on improving the paper.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

ORCID iDs

Matthias Landgraf https://orcid.org/0000-0001-9265-0681
Arpad Horvath https://orcid.org/0000-0003-1340-7099

References

[1] Maamoun N 2019 The Kyoto protocol: empirical evidence of a hidden success J. Environ. Econ. Manag. 95 227–56
[2] Mitchell D, Allen M R, Hall J W, Muller B, Rajamani L and Le Quéré C 2018 The myriad challenges of the Paris agreement Phil. Trans. R. Soc. A 376 20180066
[3] United Nations 2015 Paris Agreement https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[4] Goyal R, England M H, Sen Gupta A and Jucker M 2019 Reduction in surface climate change achieved by the 1987 Montreal protocol Environ. Res. Lett. 14 124041
[5] European Commission 2015 EU ETS Handbook (Climate Action) p 138 available from: http://ec.europa.eu/clima/policies/decarbonisation/publications/docs/ets_handbook_en.pdf
[6] European Parliament and the Council of the European Union 2018 Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union and Amending Council Directive 96/61/EC (European Parliament and the Council of the European Union)
[7] European Commission 2019 The European Green Deal Eur Comm vol 53 p 24 available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN
[8] Bloomfield J and Steward F 2020 The politics of the green new deal Polit. Q. 91 770–9
[9] Osewaarde M and Osewaarde-Lowtoow R 2020 The EU’s green deal: a third alternative to green growth and degrowth? Sustain 12 9825
[10] Federal Ministry Republic of Austria Sustainability and Tourism, Federal Ministry Republic of Austria Transport Innovation and Technology 2018 Austrian Climate and Energy Strategy (Mission 2030) 1–90 available from: www.bmivt.gv.at
[11] Austrian Environmental Agency 2019 Austrian emission factors for transport Vienna available from: https://umweltbundesamt.at/umweltsituation/verkehr/verkehrsdaten/emissionsfaktoren_verkehrsmittel/
[12] Chester M V and Horvath A 2009 Environmental assessment of passenger transportation should include infrastructure and supply chains Environ. Res. Lett. 4 24008
[13] Austrian Standards 2021 ÖNORM EN ISO 14040:2021 03 01 Environmental Management—Life Cycle Assessment—Principles and Framework ISO 14040:2006 + Amd 1:2020 available from: https://shop.austrian-standards.at/action/en/public/details/693563/OENORM_EN_ISO_14040_2021_03_01
[14] Austrian Standards 2021 ÖNORM EN ISO 14044:2021 03 01 Environmental Management—Life Cycle Assessment—Requirements and Guidelines (Austrian Standards) available from: https://shop.austrian-standards.at/action/en/public/details/693501/OENORM_EN_ISO_14044_2021_03_01
[15] Austrian Standards 2016 ÖNORM CEN ISO/TS 14071:2016 04 15 Environmental Management—Life Cycle Assessment—Critical Review Processes and Reviewer Competencies: Additional Requirements and Guidelines to ISO 14044:2006 (Austrian Standards) available from: https://shop.austrian-standards.at/action/en/public/details/508505/ONR_CEN_ISO_TS_14071_2016_04_15
[16] Austrian Standards 2020 ÖNORM EN 15804:2020 02 15 Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products (Austria: Austrian Standards)
[17] Rebitzer G et al 2004 Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications Environ. Int. 30 701–20
[18] Facanha C and Horvath A 2007 Evaluation of life-cycle air emission factors of freight transportation Environ. Sci. Technol. 41 7138–44
[19] Chester M and Horvath A 2007 Environmental life-cycle assessment of passenger transportation: a detailed methodology for energy, green-house gas, and criteria pollutant inventories of automobiles, buses, light rail, heavy rail and air UC Berkeley for Future Urban Transport (Berkeley: UC Berkeley) available from: https://escholarship.org/uc/item/5be4s1n3
[20] Chester M and Horvath A 2010 Life-cycle assessment of high-speed rail: the case of California Environ. Res. Lett. 5 014003
[21] Chester M and Horvath A 2012 High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California’s future Environ. Res. Lett. 7 034012
[22] Wang X C and Sanders I. 2012 Energy consumption and carbon footprint of high-speed rail projects: using CAHSR and FHSR as examples Proc. Inst. Mech. Eng. F 226 26–35
[23] Cortazar A, Bueno G and Hoyos D 2021 Environmental balance of the high speed rail network in Spain: a life cycle assessment approach Res. Transp. Econ. 2019 101035
[24] Bueno G, Hoyos D and Capellán-Pérez I 2017 Evaluating the environmental performance of the high speed rail project in the Basque Country, Spain Transp. Econ. 62 44–56
[25] Schmied M, Mottschall M and Löchter A 2013 Treibhausgasmmissionen durch die Schieneninfrastruktur und Schienen-fahrzeuge in Deutschland available from: https://oeko.de/oekodoc/1852/2015-520-de.pdf
[26] Westin J and Kågesson P 2012 Can high speed rail offset its embedded emissions? Transp. Res. D 17 1–7
[27] Åkerman J 2011 The role of high-speed rail in mitigating climate change—the Swedish case Europabanan from a life cycle perspective Transp. Res. D 16 208–17
[28] Yang X, Lin S, Li Y and He M 2019 Can high-speed rail reduce environmental pollution? Evidence from China J. Cleaner Prod. 239 118135
[29] Spielmann M, Bauer C, Dones R and Tuchscheid M 2007 Transport services Ecointvent Report No. 14 (Swiss Center for Life Cycle Inventories) available from: https://db.ecoinvent.org/reports/14_Transport.pdf
[30] Banar M and Özdemir A 2015 An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods Transp. Res. D 41 88–105
[31] Jones H, Moura F and Domingos T 2017 Life cycle assessment of high-speed rail: a case study in Portugal Int. J. Life Cycle Assess. 22 410–22
[32] Yue Y et al 2015 Life cycle assessment of high-speed rail in China Transp. Res. D 41 367–76
[33] Von Rozycki C, Koessner H and Schwarz H 2003 Ecology profile of the German high-speed rail passenger transport system, ICE Int. J. Life Cycle Assess. 8 83–91
[34] Facanha C and Horvath A 2006 Environmental assessment of freight transportation in US Int. J. Life Cycle Assess. 11 229–39
[35] Fries N and Hellweg S 2014 LCA of land-based freight transportation: facilitating practical application and including accidents in LCIA Int. J. Life Cycle Assess. 19 546–57
[36] Okonkwo N 2019 Life cycle assessment of rail freight transport in Belgium Clean Technol. Environ. Policy 22 1199–31
[37] Chang B and Kendall A 2011 Life cycle greenhouse gas assessment of infrastructure construction for California’s high-speed rail system Transp. Res. D 16 429–34
[38] Cheng S, Lin J, Xu W, Yang D, Liu J and Li H 2020 Carbon, water, land and material footprints of China’s high-speed railway construction Transp. Res. D 82 102314
[39] de Bortoli A, Bouhaya L and Feraille A 2020 A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours–Bordeaux railway in France Int. J. Life Cycle Assess. 25 814–30
[40] International Union of Railways UIC 2017 Carbon Footprint of High Speed Rail (International Union of Railways UIC)
[41] Asplan V 2011 Life cycle assessment of the follo line-infrastructure available from: https://banenor.no/globalassets/documents/ prosjekter/follobanen/lca—folloline-infrastrukture_en.pdf
[42] Stripple H and Uppenberg S 2010 Life Cycle Assessment of Railways and Rail Transports vol B1943 (Swedish Environmental Research Institute)
[43] Dimoula V, Khagia F and Tsalikidis A 2016 A holistic approach for estimating carbon emissions of road and rail transport systems Aerosol Air Qual. Res. 16 61–8
[44] Sasidharan M, Burrow M P N and Ghataora G S 2020 A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance Res. Transp. Econ. 80 100815
[45] Lederer J, Kleemann F, Ossberger M, Rechberger H and Fellner J 2016 Prospecting and exploring anthropogenic resource deposits: the case study of Vienna’s subway network J. Ind. Ecol. 20 1320–33
[46] Onugbenga O, Kalyvitis N and Saxe S 2019 Embodied emissions in rail infrastructure: a critical literature review Environ. Res. Lett. 14 123002
[47] Chester M V and Ryerson M S 2014 Grand challenges for high-speed rail environmental assessment in the United States Transp. Res. A 61 15–26
[48] Newman P W and Kenworthy J R 1996 The land use-transport connection Transp. Rev. 14 83–101
[49] Veit P 2007 Track quality—luxury or necessity? Maintenance and renewal J. Railw. Tech. Rev. 7 8–12
[50] Vidovic I and Landgraf M 2019 Fibre optic sensing in railway infrastructure monitoring Global Railw. Rev. 25 18-21
[51] Offenbacher S, Neuhold J, Veit P and Landgraf M 2020 Analyzing major track quality indices and introducing a universally applicable TQI Appl. Sci. 10 1–17
[52] Offenbacher S, Antony B, Barbir O, Auer F and Landgraf M 2020 Evaluating the applicability of multi-sensor equipped tamping machines for ballast condition monitoring Measurement 172 108881
[53] Landgraf M 2018 Smart data for Sustainable Railway Asset Management: Assessment—Aggregation—Asset Management (Graz: Monographic Series TU Graz) p 139
[54] Landgraf M and Hansmann F 2019 Fractal analysis as an innovative approach for evaluating the condition of railway tracks Proc. Inst. Mech. Eng. F 233 596–605
[55] Landgraf M and Enzl M 2018 Smart data for a pro-active railway asset management Proc. 7th Transport Research Arena TRA 2018 (Vienna)
[56] Neuhold J, Vidovic I and Marschnig S 2020 Preparing track geometry data for automated maintenance planning J. Transp. Eng. A 146 1–11
[57] Swedish Transport Administration 2016 EPD: Railway tunnels on Bothnia Line (International EPD Consortium) 1–8 available from: www.botniabanan.se
[58] Swedish Transport Administration 2010 EPD: Railway Track on Bothnia Line (International EPD Consortium) 1–8
[104] Krezo S, Mirza O, Kaewunruen S and Sussman J M 2018 Evaluation of CO2 emissions from railway resurfacing maintenance activities Transp. Res. D 65 458–65

[105] DG Move European Union 2015 State of the art on alternative fuels transport systems in the European Union available from: https://ec.europa.eu/transport/sites/transport/files/themes/urban/studies/doc/2015-07-alter-fuels-transport-syst-in-eu.pdf%250

[106] Rao X, Montigel M and Weidmann U 2016 A new rail optimisation model by integration of traffic management and train automation Transp. Res. C 71 382–405

[107] Ichikawa S and Miyatake M 2019 Energy efficient train trajectory in the railway system with moving block signaling scheme IEE J. Ind. Appl. 8 586–91

[108] Fernández-Rodríguez A, Cucala A P and Fernández-Cardador A 2020 An eco-driving algorithm for interoperable automatic train operation Appl. Sci. 10 1–29

[109] Zhang H, Jia L, Wang L and Xu X 2019 Energy consumption optimization of train operation for railway systems: algorithm development and real-world case study J. Cleaner Prod. 214 1024–57

[110] Passer A et al 2015 Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries Int. J. Life Cycle Assess. 20 1199–212

[111] Burchart-Korol D 2013 Life cycle assessment of steel production in Poland: a case study J. Cleaner Prod. 54 235–43

[112] Esmaeili M, Yousefian K and Nouri R 2017 Vertical load distribution in ballasted railway tracks with steel slag and limestone ballasts Int. J. Pavement Eng. 20 1–8

[113] Qasrawi H 2014 The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment Constr. Build. Mater. 54 298–304

[114] Delgado B G, Viana da Fonseca A, Fortunato E and Maia P 2019 Mechanical behavior of inert steel slag ballast for heavy haul rail track: laboratory evaluation Transp. Geotech. 20 100243

[115] Ferdous W, Manalo A, Van Erp G, Aravindhan T, Kaewunruen S and Remennikov A 2015 Composite railway sleepers—recent developments, challenges and future prospects Compos. Struct. 134 158–68

[116] Oei P Y and Mendelevitch R 2016 European scenarios of CO2 infrastructure investment Energy J. 37 171–94