Embodied emissions in rail infrastructure: a critical literature review

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Keywords: rail infrastructure, embodied greenhouse gas emissions, life cycle assessment

Abstract

This paper investigates the state of knowledge in quantifying the embodied greenhouse gas (GHG) emissions in rail infrastructure and develops a sketch model for estimating the GHG impact of rail infrastructure based on the literature. A literature review identified 22 publications, containing 57 case studies, at least touching on the embodied GHG for different types of rail infrastructure. The cases studies include high speed rail, intercity rail, light rail, commuter rail, heavy rail, freight, and metro rail. The paper examines the GHG impact per kilometre of rail infrastructure reported across the case studies and compares the boundaries, functional units, methods, and data used. Most studies employed process-based LCA for an attributional analysis. 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. However, large ranges in GHG per kilometre remain after controlling for elevated and tunnelled distance. Comparing the embodied emissions across the rail types was challenging, due to the large variations in system boundaries, study goals, and inventory methods adopted in the publications. This review highlights the need for standardization across the reporting of embodied GHG for rail infrastructure to better facilitate hot spot detection, engineering design and GHG policy decision making. The statistical model finds that overall ~941 (±168) tCO₂e are embodied per kilometre of rail at-grade, and tunneling has 27 (±5) times more embodied GHG per kilometre than at-grade construction. The statistical model is based on the findings of published literature and does not explicitly consider function, geometry, specifications, emphasis on whole lifecycle, legislative constraints, socio-economic factors, or the physical and environmental conditions of the construction site.

1. Introduction

This paper investigates the state of knowledge in quantifying the embodied greenhouse gas (GHG) emissions in rail infrastructure and develops a sketch model for estimating the GHG impact of rail infrastructure based on the literature. The embodied GHG emissions in the construction sector are defined as the emissions generated by ‘the energy consumed in the acquisition of raw materials, their processing, manufacturing, transportation to site, and construction’ and ‘the emissions incurred to maintain, repair, restore, refurbish or replace materials, components or systems during the effective life of the’ structure (Ibn-Mohammed et al 2013). In this paper we focus on embodied emissions from initial construction. A growing body of literature highlights the need to understand the embodied GHG emissions of transport infrastructure provision (Chester and Horvath 2009, Morita et al 2013). Rail infrastructure can provide an important environmental service by reducing the need for automobile-based travel, but significant embodied GHG emissions are associated with the introduction of new rail transit infrastructure through the use of large quantities of materials (e.g. steel and concrete) and fuel (e.g. transportation, on-site energy use) during construction (Chester and Horvath 2010, Westin and Kågeson 2012, Saxe et al 2017). To maximize the life cycle environmental benefit of rail infrastructure, the up-front embodied emissions must be minimized where possible. As global rail infrastructure investments grow, a baseline numerical understanding of the embodied GHG emissions is needed to inform policy makers, engineers and contractors and facilitate reductions in...
embodied GHG emissions for future rail projects, particularly at the early planning stage when project scoping is completed.

The planning and scoping phases of a construction project have the largest impact on the final overall performance of the project, as decisions at this stage largely lock in the type of project and its location (Häkkinen et al. 2013). This scoping phase occurs prior to design and construction and is when the broad objectives and the requirements (e.g. route planning) of the project are established (Ainger and Fenner 2014). The planning phase is the purview of politicians and planners. By definition, this stage does not include sufficient detailed design to allow for a case-specific assessment of material and energy needs which are necessary for case-specific detailed GHG assessment.

For rail lines, the scoping process and route selection have the largest potential to influence overall GHG emissions, as they dictate the length of rail to be constructed and the type (at-grade, elevated, tunnelled) of construction needed. Further, to explore the GHG benefit ratio or GHG payback period of a given project, the quantity of emissions associated with construction is needed but details of construction are unavailable at the key decision-making early stages. The synthesis of published work in this paper facilitates approximate early stage estimates of embodied GHG emissions. The aim of the present study is to identify and partition the embodied GHG findings from published research papers into classes of track (at-grade, tunneling, elevated) and establish a first step towards a generalized state-of-the-knowledge model of rail infrastructure embodied GHG emissions based on existing literature. This cannot and should not replace detailed case-specific GHG assessment as design progresses.

Life cycle assessment (LCA) is a holistic approach to quantify the environmental impacts of products through assessing the impact of each process in the manufacturing, operation, use and disposal of the product. The overall LCA impact is the cumulative environmental impact across all the life stages (The International Standards Organisation 2006b). Embodied GHG assessment is a subset of LCA focusing on the production of the product, in this case the rail infrastructure, and is often called cradle to gate LCA. An assessment of embodied GHG in rail infrastructure requires two main inputs, (1) detailed accounting of material and energy used and (2) the GHG intensity of materials and energy, usually reported as GHG intensity factors.

Over the last decade plus, an increase in academic and policy interests has produced a body of knowledge on the embodied GHG in rail infrastructure. This paper reviews and compares that knowledge for the range of GHG impact per kilometre of rail reported across the case studies and compares the boundaries, functional units, methods and data used. Further, this research compares different categorization criteria of rail infrastructure, working towards a general estimate of the embodied GHG emissions in rail per km. In section 6, to facilitate comparison between different rail systems with different percentages of at-grade, elevated and tunnelled segments, we convert the embodied GHG emissions to equivalent at-grade kilometres. This facilitated the development of a linear model of GHG emissions per at-grade kilometre and an assessment of the relative GHG intensity of elevated, tunnelled and at-grade rail infrastructure.

This research provides baseline formulas for preliminary assessment of embodied GHG emissions at the project scoping stage to inform the project planning process of rail infrastructure and allow for rough estimates of GHG per kilometre.

Section 2 discusses the criteria used to select the literature reviewed in this study; section 3 provides a description of the dataset; section 4 discusses the parameters influencing embodied GHG emissions in the published literature; section 5 details the findings of embodied GHG from the literature review. Section 6 develops and reports on a generalized model of GHG emissions using a conversion to equivalent at-grade kilometres to adjust for the varying distances of tunnelled, elevated and at-grade track between different case studies. Section 7 presents conclusions and goals for future research.

2. Selection of reviewed papers

In this research, we set out to identify and review a census of the last decade (post 2009) of literature quantifying the embodied GHG emissions in case study rail projects. All rail types are included in the literature review, including intercity rail, commuter rail, light rail, metro rail and freight. The papers were reviewed with a view to the following questions:

- Where in the world has embodied GHG in rail been investigated?
- What are the factors influencing the embodied GHG results in published papers?
- What are the published GHG payback periods—the operation period of rail infrastructure required to offset the embodied GHG emissions from construction?
- Does the literature provide a baseline of embodied GHG emissions in rail infrastructure that can be used to inform projects during planning?

The study started with a keyword search for rail, embodied and GHG in scientific research databases, primarily Scopus and Science Direct. Keywords were also searched on Google Scholar and OneSearch, the University of Toronto’s Library journal search platform. Additional publications were gathered through cross-referencing. Our search on Scopus identified 133 research articles from 2009 to 2018. A search for
similar keywords in Science Direct found 451 research articles between 1994 and 2018. Publishing on this topic has increased significantly since 2009 and the seminal work by Chester and Horvath (2009). An abstract review was carried out on these initially identified publications. Publications that did not deal with rail and embodied emissions were eliminated (e.g. papers dealing with transportation fuels); publications pre-2009 (with the exception of Lave (1978) which is a key early payback analysis paper) were excluded. After initial review, 100 publications dealing with environmental life cycle assessment, embodied GHG and/or reducing the GHG of rail infrastructure were selected for full paper review. Throughout, a spreadsheet of considered papers was maintained and updated by the authors. These 100 papers were further reduced based on whether the paper (1) deals with embodied impacts, (2) contains real world data from at least one specific case study, and (3) communicates the results with sufficient detail to allow review (e.g. scope, functional unit, and methods are communicated or at a minimum implied).

This study did not consider studies where it was not possible for a reader to calculate the embodied GHG emissions separately from operational emissions (Akerman 2011, Pan et al 2013, Tarnoczi 2013, Warren and Jeromonachou 2013, Timmermann and Dibdakov 2014, Matan et al 2015, Steffen et al 2015, Krezo et al 2016, Dalkic et al 2017) or studies which did not consider non-operational emissions (Cárdenas et al 2016, Dalkic et al 2017, Sarigiannis et al 2017, Prussi et al 2019). Studies which were not project-based, but either country-based and/or sector-based (Yang et al 2009, McCollum and Yang 2009, Nelldal and Andersson 2012, Pan et al 2013, Warren and Jeromonachou 2013, To 2015, Cheng et al 2016, De Andrade and D’Agosto 2016, Mulley et al 2017, Spears et al 2017, Toledo and Rovere 2018) were similarly not considered. This study focused on post 2009 papers, so older papers (von Rozycki et al 2003) were excluded.

The final body of literature consisted of 22 publications, including 57 unique infrastructure cases, which were used to develop a database reporting the key elements of published embodied GHG assessment in rail infrastructure. Since the data were collected by the authors of the respective publications, they are considered as secondary data (Irwin 2013). By its nature, the quality of the secondary data cannot be verified and the data are dependent on the assumptions and preconceptions of the authors who generated them (Irwin 2013). The reviewed publications are listed in table 1.

3. Description of dataset

The 57 reviewed case studies represent 7 types of rail infrastructure, as identified by the original authors, including High Speed Rail (HSR), Commuter Rail, Heavy Rail Transit (HRT), Light Rail Transit, Intercity, Metro Rail and Freight Rail from 3 continents and 19 cities. High speed rail (HSR) is a form of mass transit that operates significantly faster than traditional rail traffic; trains that run consistently faster than 200 km h⁻¹ are called high speed (Agarwal 2011). Commuter rail is ‘a passenger rail transport service operating between a city center to outer suburbs’ (MDOT—Michigan Department of Transportation 2014, Credit 2019). Light rail transit system is a form of mass transit with a smaller passenger capacity compared to other rail systems and uses electric powered trains (Durand et al 2016). Heavy-rail transit has larger passenger capacities than light rail and usually runs in its own right of way (Hunter-Zaworski 2017, Credit 2019). Intercity rail is a passenger rail service between cities or metropolitan areas (Federal Railroad Administration 2017). Metro rail is a passenger rail system, mostly operated with electric trains and grade separated from other traffic, either underground (in tunnels) or above ground (elevated) (Sharma et al 2013). Finally, freight rail is a cargo rail service, usually intercity, and generally does not carry human passengers (Zunder et al 2016).

Six of the considered papers (National Rail 2009, Chester and Horvath 2010, Chester et al 2012, 2013, Yue et al 2015, Chester and Cano 2016) presented a scenario analysis of the same rail line changing infrastructure approaches (e.g. light rail, metro rail, tunneled, at-grade) and/or other non-infrastructure factors (e.g. train type). From these papers, only the infrastructure scenarios have been included in our case study database. Forty-four percent of the cases were HSR, nineteen percent intercity rail, twelve percent light rail, eleven percent commuter rail. The remaining case studies were heavy rail transit (HRT—7%), Metro rail (5%) and freight rail (2%) infrastructure. Twenty-eight (46%) of the case studies are from Europe (20 from the UK), nineteen (33%) of the case studies are from the North America (18 from the US and 1 from Canada), and the remaining 10 (18%) are from Asia as illustrated in figure 1.

The length of the case studies ranges from 0.3 to 1318 km; the average length of the rail infrastructure studied is 476 km and the median length is 401 km. The analysis period adopted in the case studies ranges between 20 and 100 years. There is large heterogeneity of analysis approaches, analysis periods, rail types and methodologies within the dataset, including within case studies from the same country. By focusing on embodied GHG emissions, this paper is focused on initial construction of the studied rail lines and is less subject to the wide ranges in temporal assumptions in the papers. However, the amount of time the initial construction would last, e.g. the durability of the rail line, is an important consideration of life time GHG emissions, affecting how much maintenance and replacement will be needed. A detailed consideration of long-term durability is outside the scope of this.
Table 1. Reviewed literature: publication title; publication authors, rail types, functional unit, length and amortization period of case study.

| Author (Ab) | Publication Title | Country/Region | Type of Rail | Rail length (km) | Functional units | Adopted infrastructure life time (Years) |
|-------------|-------------------|----------------|--------------|------------------|------------------|----------------------------------------|
| Lave (1978) | Transportation and energy: some current myths | USA/San Francisco | HRT | 180 | 1 PMT | N/A |
| National Rail (2009) | Comparing environmental impact of conventional and high-speed rail | UK | 9"Intercity"9"HSR | 185–764 | 1 PKT | N/A |
| Chester and Horvath (2010) | Life cycle assessment of high-speed rail: the case of California | USA/California | 3"HSR | 1100 | 1 VKT/1 PKT. | 100 |
| Chester and Horvath (2010) | Life cycle assessment of high-speed rail: the case of California | USA/California | 3"HRT | 710 | 1 VKT/1 PKT. | 100 |
| Chang and Kendall (2011) | Life cycle greenhouse gas assessment of Infrastructure construction for California’s high-speed rail system | USA/California | HSR | 725 | 1 PKT | 60–100 |
| Paris and de Silva (2010) | CROSSRAIL, Carbon footprint study—methodology and results | UK/Tottenham | Metro | 118 | 1 PKT | 120 |
| Westin and Kågeon (2012) | Can high speed rail offset its embedded emissions? | (Europe) | HSR | 500 | 1 PKT | 50 |
| Chester et al (2012) | Environmental Life-cycle Assessment of Los Angeles Metro’s Orange Bus Rapid Transit and Gold Light Rail Transit Lines | USA/LA | 2"Light | 31.7 | 1 PMT | 30 |
| Chester et al (2013) | Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals | USA/LA | 2"Light | 20.8 | 1 PMT | 100 |
| Morita et al (2013) | A Study on the Methodology for Evaluating the Environmental Load of Rail Infrastructure Construction | Japan/Tokyo | Light | 33 | 1 RIS | 50 |
| Hanson et al (2016) | Greenhouse gas emissions associated with materials used in commuter rail lines | USA/New Jersey | 5"Commuter | 6–196 | 1 TMT | 50 |
| Lederer et al (2016) | The life cycle energy demand and greenhouse gas emissions of high capacity urban transport systems: A case study from Vienna’s subway line U2 | Austria/Vienna | Light | 14.8 | 1 PKT | N/A |
| Miyoshi and Givoni (2014) | The Environmental Case for the High-Speed Train in the UK: Examining the London-Manchester Route | UK/London | HSR | 351.7 | 1 PKT | 30–100 |
| Yue et al (2015) | Life Cycle Assessment of High Speed Rail in China | China/Beijing | 6"HSR | 1318 | 1 PKT | 20 |
| Infraestructuras (2015) | Environmental Product Declaration of ‘Arroyo Valchano’ railway bridge | Spain/Madrid | HSR | 0.3 | 1 MOB | 60 |
| Jones et al (2017) | Life Cycle Assessment of High-Speed Rail: A case study in Portugal | Portugal/Lisbon | HSR | 297 | 1 PKT | 35 |
| Li et al (2016) | Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro | China/Shanghai | Metro | 528 | 1OCL | 50 |
| Chester and Cano (2016) | Time-based life-cycle assessment for environmental policymaking: Greenhouse gas reduction goals and public transit | USA/LA | Light | 24.4 | 1 PKT | 28 |
| International Union of Railways (2016) | Carbon footprint of Railway Infrastructure. Comparing existing methodologies on typical corridors | Japan | HSR | 554 | 1 PKT | 60 |
| International Union of Railways (2016) | Carbon footprint of Railway Infrastructure. Comparing existing methodologies on typical corridors | Netherlands | Intercity | 30 | 1 PKT | 55 |
| International Union of Railways (2016) | Carbon footprint of Railway Infrastructure. Comparing existing methodologies on typical corridors | Sweden/Bothnia | Freight | 209 | 1 PKT | 40 |
| Dimoula et al (2016) | | Greece/Thessaloniki | Intercity | 442 | 1 RIS | N/A |
| Author (Ab) | Publication Title | Country/Region | Type of Rail | Rail length (km) | Functional units | Adopted infrastructure life time (Years) |
|------------|-------------------|----------------|--------------|------------------|------------------|-----------------------------------------|
| Bueno et al (2017) | Evaluating the environmental performance of the high-speed rail project in the Basque Country, Spain | Spain/Basque | HSR | 180 | 1 PKT | 60 |
| Saxe et al (2017) | The net greenhouse gas impact of the Sheppard Subway Line | Canada/Toronto | Metro | 5.5 | 1 SS | N/A |
| Shinde et al (2018) | Life Cycle Analysis based Comprehensive Environmental Performance Evaluation of Mumbai Suburban Railway, India | India/Mumbai | Commuter | 983.8 | 1 PKT | 25 |

2* means two case studies were present in the publication.
3* means two case studies were present in the publication.
PKT (Passenger kilometre travelled); PMT (Passenger mile travelled); VKT (Vehicle kilometre travelled); TMT (Track mile travelled), RIS (Rail Infrastructure system), MOB (Metre of bridge); CL (Kilometre of construction length), SS (Subway system); HSR (High Speed Rail).
review, as it is generally not explored in detail in the reviewed papers.

The examined papers completed embodied GHG/LCA assessments based on data collected at different points during the case study planning and construction. Twenty-three percent of the case studies were carried out during the proposed phase, before final designs were selected or construction started. Nine percent were in construction when they were studied. The remaining sixty-eight percent of the case studies were analyzed after they were completed. Assuming perfect data access, the completed projects have the potential to have the highest accuracy and least uncertainty, given details of construction were set and could be measured. During the planning stage, a large uncertainty would be expected as the final details of construction and material use are not yet fully determined. However, in practice, many of the authors note that access to the data for their case studies and details of material and fuel use were challenging, irrespectively of the project stage.

4. Comparison of published case studies

The case studies are compared along key characteristics of an LCA study (e.g. scope, functional unit) and were analysed quantitatively and qualitatively in order to facilitate comparison. Where possible, published supplementary data or personal communication with the authors were referenced to collect more detailed information not available in the main body of the paper (Chester and Horvath 2009, 2010, Chester et al 2012, Kimball et al 2013, Jones et al 2017). The scope, functional unit and type of rail studied are reported throughout this review as defined in the original papers. Across the case studies, the rail infrastructure dimensions were obtained from Google Earth, Google Maps, Construction documents, and Preliminary bid documents available to the researchers (Infraestructuras 2015, Dimoula et al 2016, Shinde et al 2018). Embodied GHG emissions from the different case studies are converted to per kilometre for comparison below using the length of infrastructure reported in the paper or collected from publicly available data. The proportion of at-grade, elevated and/or tunneled length was gathered from publicly available data for built and planned infrastructure when not specifically stated in the original paper.

A range of rail infrastructure types was reviewed, from light rail to high speed intercity rail. The infrastructure types considered in the 57 case studies are shown in table 3. The reviewed papers generally reported what type of rail they investigated (e.g. metro, HSR, light rail). While rail type is often a proxy for construction type (subways are often underground, light rail is often at-grade), many of the case studies had exceptions to these rules (Chester and Horvath 2010, Morita et al 2013, Jones et al 2017). Perhaps unsurprisingly, our review indicates that more than being determined by the type of rail, the embodied GHG is driven by the type of construction (at-grade, underground, elevated); this is discussed further in section 6. The different papers communicated the type of rail infrastructure in different ways, some reported a fraction of the infrastructure as tunnels, bridges, or at-grade (Morita et al 2013, International Union of Railways 2016). Others reported detailed infrastructure information extracted from construction documents (Chang and Kendall 2011, Lederer et al 2016).

In line with this review topic most of the papers focused on GHG emissions. The considered GHG
emissions are commonly CO$_2$, N$_2$O and CH$_4$ (Chester 2008).

4.1. Research goals
In the reviewed papers the degree of focus on embodied GHG assessment and reporting varied. For some papers it was the main focus; for others an aside or a step towards the main goal. Reported detail and space dedicated to the embodied GHG assessment in the paper followed the main purpose of the papers. Overall, the reviewed papers pursued four main research goals:

- To understand the environmental impact from the construction of rail infrastructure.
- To identify the relative environmental impact of the different life stages of transport infrastructure (e.g. construction versus operation).
- To compare the relative environmental impact of different types of transport infrastructure (e.g. rail versus road).
- To understand the environmental payback period of rail transport infrastructure.

Table 2 lists the main goal of the reviewed literature. Some papers had multiple stated goals and are listed more than once.

The goals of each study influenced the analysis methods chosen, the scope of data gathered, and the attention given to embodied emissions in the publications. This, in turn, affects the comparability of the case studies. Publications whose main goal was to examine the embodied GHG of the infrastructure included more detail on infrastructure construction and embodied GHG emissions (Chang and Kendall 2011, Infraestructuras 2015, Yue et al 2015, Hanson et al 2016), whose papers compared rail infrastructure with other transport infrastructure, focused their comparison on life stages where data were available for all the compared infrastructures. Chang and Kendall (2011), whose paper focuses on the payback period, presented a detailed model of the global warming effect using cumulative radiative forcing to calculate the payback period and mostly discuss payback related data.

While 22 papers at least touch on embodied GHG for rail, only 4 papers have made it the main focus. It was not practical to limit the review to this small number of papers. The limited number of embodied-GHG focused papers is likely due, in part, to the challenges of gathering detailed design or construction data for rail infrastructure projects. This challenge is reported in many of the reviewed papers and is an impediment to further research and development in this field.

4.2. Functional unit
The definition of a functional unit is a central requirement of LCA (The International Standards Organisation 2006a, 2006b). The functional unit defines the purpose of the product and facilitates comparisons between different products that provide similar functions. A range of functional units was used across the reviewed studies. The most common functional units employed were passenger kilometre/mile travelled (PKT/PMT), particularly for papers comparing different types of transport infrastructure. Others include track kilometre/mile travelled, overall construction length, vehicle kilometre travelled (VKT), track mile travelled (TMT), the rail infrastructure system (RIS), the meter of bridge (MOB), the kilometre of construction length (CL) and the subway system (SS) as shown in figure 2. In cases where the functional unit was not explicitly stated, the implied unit of analysis is reported (e.g. one subway line) (Dimoula et al 2016, Saxe et al 2017).

The functional unit is critically used for normalization of GHG impacts and comparison to competing products. However, in the case of rail infrastructure which can be built in many different ways in many different conditions (e.g. soil types, elevation changes), it is challenging to clearly define and capture a well

| Research goals | Publication |
|----------------|-------------|
| Identify environmental impact of the construction of the rail infrastructure. | (von Rozycki et al 2003, Åkerman 2011, Chang and Kendall 2011, Infraestructuras 2015, Yue et al 2015, Hanson et al 2016) |
| Identify the relative environmental impact of the different life stages of transport infrastructure. | (Morita et al 2013, Miyoshi and Givoni 2014, Chester and Cano 2016, Bueno et al 2017, Jones et al 2017, Saxe et al 2017, Shinde et al 2018) |
| Compare rail infrastructure with other transport infrastructure. | (Chester and Horvath 2010, Åkerman 2011, Chester et al 2012, Westin and Kågeson 2012, Morita et al 2013, Chester and Cano 2016, Dimoula et al 2016, International Union of Railways 2016, Lederer et al 2016, Li et al 2016) |
| Understand the environmental payback period of rail transport infrastructure. | (Lave 1978, Chester and Horvath 2010, Chang and Kendall 2011, Chester et al 2012, 2013, International Union of Railways 2016, Saxe et al 2017) |
defined and complete function. For example, is the function of a metro line to move people 5 km, 5 km underground or 5 km underground through rock?

In the adoption and use of functional units across the reviewed papers, there was a significant heterogeneity in the ways infrastructure construction types (at-grade, elevated tunneled) are represented in the functional unit. In case studies looking at shorter sections of rail infrastructure the challenge of using one functional unit across different types of construction was avoided as these case studies had, for example, exclusively tunneling (Saxe et al 2017), or exclusively elevated sections (Infraestructuras 2015). For longer case studies, the differences in function provided by different types of construction were universally not discussed. Similarly, the differences in external factors like ground conditions and elevation changes were not included in functional unit definitions.

The challenge in identifying the functional units for rail infrastructure complicates comparison of embodied GHG emissions. For instance, a tunnel through competent rock will require different quantities of construction materials than one through clay, a nuance that is lost if a PKT or similar functional unit is adopted. Further, one PKT (or VKT) often used to compare between lines and modes is sensitive to the route travelled; a more direct route would have fewer PKT, a meandering one more PKT. Focusing on PKT could therefore mask important implications of construction route choice. For example, a tunnel would reduce the total length of the rail infrastructure but potentially increase the overall need for materials. The PKT would be lower in the tunnel scenario but the overall function of the rail line little changed. PKT is dependent on ridership often more than infrastructure, a challenge when the goal is embodied GHG assessment which is infrastructure focused. The GHG emissions generation of infrastructure life-cycle components, such as station construction, track/power construction, station lighting station escalators, station train controls, station parking lighting, station

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**Figure 2.** Different functional unit in papers and case studies.

| Functional Units | 1PMT | 1PKT | 1VKT | 1RIS | 1TMT | 1MOB | 1CL | 1SS |
|------------------|------|------|------|------|------|------|-----|-----|
| Number of Publications | 3    | 16   | 2    | 2    | 1    | 1    | 1   | 1   |
| Number of Case Studies | 5    | 42   | 6    | 2    | 5    | 1    | 1   | 1   |

PKT (Passenger kilometre travelled); PMT (Passenger mile travelled); VKT (Vehicle kilometre travelled); TMT (Track mile travelled), RIS (Rail Infrastructure system), MOB (Metre of bridge), CL (Kilometre of construction length), SS (Subway system)

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**Figure 3.** LCA Methods used in case studies.

- Parametric LCA: a method that specific system parameters are statistically modelled to calculate emissions
- Simplified LCA: compares the environmental impact of the rail infrastructure and no rail infrastructure condition
- Pseudo LCA: a methodology based on a mix of primary data and data from literature to calculate the GHG emissions
- Process-based LCA: a methodology performed by characterizing “all processes associated with all life cycle phases of the project”
- Hybrid LCA: incorporating both economic input-output analysis and process-based
miscellaneous, are not dependent on ridership since they need to operate regardless of the use (International Union of Railways 2016). Additionally, the use of project scale functional units—like one subway line—are hard to compare as projects vary in length, specification and long-term carrying capacity. In this paper, we normalize to kilometre of rail (or equivalent at-grade kilometre which accounts for differences between elevated, tunneled and at-grade construction) given that embodied GHG emissions are strongly dependant on material and construction energy use, which are highly correlated to construction length. For embodied GHG emissions, the use of construction length (measured in kilometre or equivalent kilometre) is a reasonable generalizable function unit. Differences in geology and associated material needs, however, remain outside this functional unit. Given available details on ground conditions for the published case studies, controlling for differences in ground conditions was not within the scope of this review. Specific communication of ground conditions is something to be added to future work in this field.

4.3. Scope and boundaries
System boundary definitions are also a foundational aspect of LCA (The International Standards Organisation 2006a, 2006b). Equivalent system boundaries are important for comparison, and for the usefulness of past models to future predictions. This review focuses on the GHG emissions produced throughout the manufacturing of materials and construction of rail infrastructure—the GHG embodied in the infrastructure after construction. All reviewed studies deal with embodied GHG, while many also included other life stages (e.g. operation). Table 3 illustrates the life stages examined in each paper. As mentioned above, four papers were focused on embodied GHG emissions and included no other life stage. Sixteen papers include the operation and maintenance phases. Two papers include the disposal phase. Within the embodied GHG assessment, the papers varied in the details of infrastructure included. A full operational rail system includes trackbeds, stations, bridges, and tunnels. In addition, different ways of reporting the system boundaries were adopted across publications. In some cases, the boundary was unclear or unspecified, for example if bridges along the rail line were included in the assessment (Jones et al 2017) or the number of the stations taken into consideration (Li et al 2016). In some cases it was unclear if pre-existing infrastructure (e.g. the Figueroa Tunnel in California (Chester and Cano 2016)) was included in the analysis of embodied GHG.

The emissions considered were associated with a range of types of infrastructure, such as trackbeds, stations, bridges and tunnels, but not all the case studies considered the same type of infrastructure (see table 3). The review is based on the embodied GHG emissions reported by the authors and as such is subject to the variation in boundaries. The embodied GHG emissions were not reported in enough detail in most papers to allow standardization of boundaries between papers. This is a key limitation of the publishing in this field.

4.4. Life cycle assessment methods
There are a variety of accepted LCA approaches, ranging from bottom up assessments like process based LCA, to top down assessments like input-output LCA. The choice of LCA method has implications for data requirements and assessment boundaries as well as for the final results. Different LCA methods were used in the different case studies (see figure 3). Thirty-four percent of the case studies used process-based LCA, a bottom up methodology performed by mapping and characterizing ‘all processes associated with all life cycle phases of the project’ (Jones et al 2017). Hybrid LCA method were used in sixteen percent of the case studies incorporating both top down economic input-output analysis-based (sector-by-sector wider analysis) and process-based LCA (Chester and Horvath 2010) in an effort to recover the lack of data when data were available only for a part of the whole process or to expand the boundaries of analysis (Jones et al 2017). Thirteen percent of the case studies were analyzed using pseudo LCA methods based on a mix of primary data and data from literature to calculate the GHG emissions. Where system data were not readily available, simplified and parametric LCA approaches were adopted (Westin and Kågeson 2012, Bueno et al 2017). Simplified LCA was carried out by comparing the environmental impact of the rail infrastructure and no rail infrastructure condition within a given area (Bueno et al 2017). In parametric LCA, specific system parameters were statistically modelled to calculate emissions associated with the system. In one case study, energy per seat kilometres required to move passengers was adopted in the parametric method used to study a 500 km HSR line (Westin and Kågeson 2012). Figure 1 illustrates the LCA methods used in the case studies by rail type.

The LCA method influences the uncertainty associated with the embodied emissions result recorded in publications. Hybrid LCA method incorporates economic and system data in a bid to analyzed the environmental impact of a system (Chester and Horvath 2010, Paris and de Silva 2010, Chester et al 2013), and is applied when there is lack of primary data at the process based level or to expand boundaries beyond where process based level detail is available (Jones et al 2017). Process-based LCA incorporates emissions from system information with less uncertainty than hybrid since process-based LCA allows a detailed analysis (Jones et al 2017) but often deals with a more limited scope to facilitate data collection. Hybrid and process-based LCA require a large amount
### Table 3. Case study construction phase, Infrastructure types, and system boundaries.

| Author (Ab)               | Type     | Construction phase | Infrastructure analyzed | System boundaries |
|---------------------------|----------|--------------------|-------------------------|-------------------|
|                           |          | Proposed Under-construction Constructed | Trackbeds Stations Bridges Tunnels | Construction Operation Maintenance Disposal |
| Lave (1978)               | HRT      | x                  | x                       | x    | x    | x    | x    |
| National Rail (2009)      | Intercity | x                  | x                       | x    | x    | x    | x    |
| Chester and Horvath (2010)| 3rd HRT  | x                  | x                       | x    | x    | x    | x    |
| Chang and Kendall (2011)  | HSR      | x                  | x                       | x    | x    | x    | x    |
| Paris and de Silva (2010) | Metro    | x                  | x                       | x    | x    | x    | x    |
| Westin and Kågeason (2012)| HSR      | x                  | x                       | x    | x    | x    | x    |
| Chester et al (2012)      | 2nd Light| x                  | x                       | x    | x    | x    | x    |
| Chester et al (2013)      | 2nd Light| x                  | x                       | x    | x    | x    | x    |
| Morita et al (2013)       | Light    | x                  | x                       | x    | x    | x    | x    |
| Hanson et al (2016)       | 5th Commuter | x                  | x                       | x    | x    | x    | x    |
| Lederer et al (2016)      | Light    | x                  | x                       | x    | x    | x    | x    |
| Miyoshi and Givoni (2014) | HSR      | x                  | x                       | x    | x    | x    | x    |
| Yue et al (2015)          | HSR      | x                  | x                       | x    | x    | x    | x    |
| Infraestructuras (2015)   | HSR      | x                  | x                       | x    | x    | x    | x    |
| Jones et al (2017)        | HSR      | x                  | x                       | x    | x    | x    | x    |
| Li et al (2016)           | Metro    | x                  | x                       | x    | x    | x    | x    |
| Chester and Cano (2016)   | Light    | x                  | x                       | x    | x    | x    | x    |
| International Union of Railways (2016) | HSR, Intercity | x                  | x                       | x    | x    | x    | x    |
| International Union of Railways (2016) | Freight | x                  | x                       | x    | x    | x    | x    |
| Dimoula et al (2016)      | Commuter | x                  | x                       | x    | x    | x    | x    |
| Bueno et al (2017)        | HSR      | x                  | x                       | x    | x    | x    | x    |
| Saxo et al (2017)         | Metro    | x                  | x                       | x    | x    | x    | x    |
| Shinde et al (2018)       | Commuter | x                  | x                       | x    | x    | x    | x    |
of primary system data. Pseudo LCA uses cross-referencing to estimate emissions with the associated uncertainty of applying factors developed on one case study to another, often in different conditions, for example, in a different county, or different ground conditions (Hanson et al 2016). Parametric requires modelling one or two system specific data to approximately determine the emissions associated with the system (Westin and Kågeson 2012). As the methods move from parametric to process-based, the amount of data included increases, which, in theory, decreases the uncertainty in the results. Generally, bottom up methods like process based LCA are associated with lower bound assessments and top down approaches like input-output LCA are associated with upper bound assessments.

The majority of the papers took an attributional approach to examining the GHG impact of the infrastructure; those that dove into consequential analysis focused on the consequences for travel behavior and/or land use intensification. Despite the differences between the methods, they all use emission intensities (e.g. the GHG intensity of concrete per unit) for the processes or data of interest. All the emission intensities used come from existing databases or other publications by third parties, meaning that the factors may be interrelated as they come from the same pool.

4.5. Data collection

Two main types of data were used for the studied embodied GHG assessments: (1) quantities of materials and energy used in construction, and (2) characterization factors for the GHG intensity of materials and energy used. Table 4 lists data sources and type used in the reviewed papers. For the quantity data, seven of the case studies were based on primary data from a given rail project. Primary project data collection included bills of quantity (Infraestructuras 2015, Li et al 2016, Saxe et al 2017), bidding documents of the construction project (Lederer et al 2016) and activities schedule (Miyoshi and Givoni 2014, Infraestructuras 2015, Yue et al 2015, Lederer et al 2016, Saxe et al 2017, Shinde et al 2018). Many of the papers used secondary data for estimates of material or energy use in construction relying on published relationships from other projects. A number of the papers cross referenced other papers in this study for estimates of material and fuel use required for rail infrastructure construction. Some of the researchers interviewed construction personnel and visited construction sites to obtain relevant data that helped them in their study (Miyoshi and Givoni 2014, Lederer et al 2016, Shinde et al 2018).

The material and energy characterization factors were collected from environmental LCA databases such as Ecoinvent (National Rail 2009, Chester and Horvath 2010, Yue et al 2015, Jones et al 2017), GEMIS, Chinese Core Life Cycle Database, and PE Database integrated with GaBi LCA analysis tools (Infraestructuras 2015, Yue et al 2015, Lederer et al 2016). Electricity GHG characterization data and area data were obtained from government publications and local authorities, for example for the environmental life-cycle assessment of Los Angeles Metro’s Orange Bus Rapid Transit and Gold Light Rail Transit Lines energy data were obtained by Los Angeles Department of Water and Power (Chester et al 2012). Rail projects exhibit a wide range of length and size scales. The traditional databases focus on elements with a much smaller magnitude than infrastructure projects and as such do not account for the scale of variability present in a large-scale project (e.g. the impact of year of manufacture on concrete GHG intensity). Calculating the emissions at scales larger than the ones presented in traditional databases is subject to uncertainty due to scale-up of LCA properties compounded with the influence of heterogeneity on materials and energy.

In most of the cases, the GHG intensity factors share a common starting point, using the Ecoinvent database (National Rail 2009, Chester and Horvath 2010, Paris and de Silva 2010, Chester et al 2012, 2013, Kimball et al 2013, Yue et al 2015, Chester and Cano 2016, International Union of Railways 2016). Although the GHG intensity factors are always drawn from a database, the unique characteristics of each case study influences the way data are treated in terms of normalization and weighting, affecting not only the final results but the LCA process as well. Some papers had a much broader conception of the whole LCA process, by outlining the material manufacturing information and taking into consideration the construction documents, while other papers limited their scope of analysis to available data. For example, Westin and Kågeson (2012) assumed that all parameters were triangle distributed with a lowest, a highest and a central or most likely value for each parameter needed based on data from previously published papers. In National rail (2009), where data for specific materials was not available, proxy data have been used when possible based on the closest equivalents. Dimoula et al (2016) calculated the GHG emissions based on available data—mostly operational data—from Greece.

The range in data sources and approaches introduces irreducible heterogeneity to the case studies, as they are based on different background systems with different GHG intensities. The mix of primary and secondary data within the case studies is particularly telling as it reduces the independence of the individual data points. We have not removed the studies with secondary data from this review due to the small number of overall case studies. The use of proxy data is also common, indicating that the field would benefit by more specific data on both material and fuel use in construction and specific GHG intensity factors for material and fuel use in rail projects. These challenges stem from the nature of trying to capture detailed information about large fast-moving projects. Modeling the generation of embodied GHG emissions of...
Table 4. LCA analysis tools and data source.

| Author (Ab)                  | LCA analysis tools | Data sources |
|------------------------------|-------------------|--------------|
|                              | SimaPro | GaBi | Others* | Databaseb | Construction documents | Government publications | Material manufacturing information | Peer reviewed publications | Others data sources^c |
| Lave (1978)                  |         |     |         |          |                   | x                   |                        | x                        |                         |
| National Rail (2009)         |         |     |         |          |                   | x                   |                        | x                        |                         |
| Chester and Horvath (2010)   |         |     |         |          |                   | x                   |                        | x                        |                         |
| Chang and Kendall (2011)     |         |     |         |          |                   | x                   |                        | x                        |                         |
| Paris and de Silva (2010)    |         | x    | x       |          |                   | x                   |                        | x                        |                         |
| Westin and Kåge son (2012)   |         |     |         |          |                   | x                   |                        | x                        |                         |
| Chester et al (2012)         |         |     |         |          |                   | x                   |                        | x                        |                         |
| Chester et al (2013)         |         |     |         |          |                   | x                   |                        | x                        |                         |
| Morita et al (2013)          |         |     |         |          |                   | x                   |                        | x                        |                         |
| Hanson et al (2016)          |         |     |         |          |                   | x                   |                        | x                        |                         |
| Lederer et al (2016)         |         |     |         |          |                   | x                   |                        | x                        |                         |
| Miyoshi and Givoni (2014)    |         |     |         |          |                   | x                   |                        | x                        |                         |
| Yue et al (2015)             |         |     |         |          |                   | x                   |                        | x                        |                         |
| Infraestructuras (2015)      |         |     |         |          |                   | x                   |                        | x                        |                         |
| Jones et al (2017)           |         |     |         |          |                   | x                   |                        | x                        |                         |
| Li et al (2016)              |         |     |         |          |                   | x                   |                        | x                        |                         |
| Chester and Cano (2016)      |         |     |         |          |                   | x                   |                        | x                        |                         |
| International Union of Railways (2016) |     |     |         |          |                   | x                   |                        | x                        |                         |
| International Union of Railways (2016) |     |     |         |          |                   | x                   |                        | x                        |                         |
| International Union of Railways (2016) |     |     |         |          |                   | x                   |                        | x                        |                         |
| Dimoula et al (2016)         |         |     |         |          |                   | x                   |                        | x                        |                         |
| Bueno et al (2017)           |         |     |         |          |                   | x                   |                        | x                        |                         |
| Saxe et al (2017)            |         |     |         |          |                   | x                   |                        | x                        |                         |
| Shinde et al (2018)          |         |     |         |          |                   | x                   |                        | x                        |                         |

* Other Software includes Spreadsheet, PALATE, GREET, AggRain CO₂ Tools, Statistical Simulations.

^ Other Data Sources includes Google Map, Google Earth, Interviews, Email.

# Other Databases includes EcoInvent, GEMIS, Chinese Core Life Cycle Database, PE Database.
large scale rail infrastructure requires proper representation of multi-scale heterogeneity taking into account its interaction with underlying data sources.

4.6. The use of linearity assumptions
A fundamental assumption used across all the referenced literature is that assessed representative relationships (e.g. for material use, construction approaches, GHG intensity) can be scaled up linearly from a sub sample of the assessed infrastructure to the full project. In many cases, this has been done to adjust for the challenges inherent to detailed material accounting for large projects where data is often difficult to collect. For example, in Chester (2008) the steel intensity of elevated structures is calculated using a linear relationship for steel per foot based on the steel need from a typical drawing from 1915. The steel shown in this drawing of 2250 lbs of per linear foot is scaled over a full project. Given the foundational nature of Chester (2008) this relationship has been either explicitly or through reference used in other papers (Chester and Horvath 2010, Chester et al 2012, Kimball et al 2013, Chester and Cano 2016, Saxe et al 2017). Similar linear assumptions are made to assess the use of materials in most of the reviewed papers. For example, concrete (Chester 2008, National Rail 2009, Chang and Kendall 2011, Hanson and Noland 2015, International Union of Railways 2016, Jones et al 2017), steel (Chester 2008, National Rail 2009, Chang and Kendall 2011, Hanson and Noland 2015, International Union of Railways 2016, Jones et al 2017), copper (Hanson and Noland 2015), aluminum (Hanson and Noland 2015), salt for snow melting (Chester 2008), and/or the application of parts of the rail infrastructure such as track construction (Chester 2008, Hanson and Noland 2015, Jones et al 2017), lighting (Chester 2008), parking space (Chester 2008, Hanson and Noland 2015, International Union of Railways 2016). The linearity assumption has a number of limitations, for example, different parts of a studied project use materials differently, particularly if the project is large or long. The design of one station does not necessarily accurately predict the material use of all other stations. The heterogeneity of the materials applied within the same project is also not taken into consideration. Similar concerns apply to construction energy use like fuel consumption. This introduces an uncategorized element of uncertainty to all the reviewed papers.

In future work, efforts should be made to capture a wider sample of large projects to reflect heterogeneity as, for example, ground conditions, construction approaches, design, materials and fuel use vary across projects. Researchers should explicitly consider the appropriateness and implications of linear assumptions. Rail authorities and contractors have an important data sharing role to play here as the challenge in collecting data is noted by multiple authors as a driver for using a subset of data and linear assumptions.

5. Reported embodied GHG

Figure 4 illustrates the embodied emissions reported in the reviewed literature categorized by rail infrastructure type. In this first instance, we present the embodied GHG as reported in the original papers without partitioning for construction type. HSR has the highest number (25 out of 57) of published case studies with published embodied emissions ranging from 13 tCO₂e km⁻¹ to 16 940 tCO₂e km⁻¹. The extrema (maximum) in the HSR boxplot diagram (see figure 4) is the Japan HSR system which primarily consists of tunnels and bridges. The large variation in HSR embodied GHG emissions were due to different...
assumptions across the case studies and the different need for supporting infrastructure (e.g. bridges, tunnels) in the rail system. Emissions associated with the HSR tunnel equipment (signalling, energy, wired arteries; routes, catenary, works base; buildings; telecommunications; traction power; electrical substations; equipment signals and Hot Box Detector HBD) is twice that of the equipment used for the aerial infrastructure (Chang and Kendall 2011). Japan HSR, which requires a large amount of tunneling and elevated rail given the topography of Japan, has the highest GHG emissions with a calculated value of 17 000 t CO\textsubscript{2}ek m\textsuperscript{−1} (International Union of Railways 2016).

The five US commuter rail were studied in one publication, and their embodied emissions range from 1104 to 6308 t CO\textsubscript{2}ek m\textsuperscript{−1} (Hanson et al 2016). The eleven intercity rail lines were analyzed all located in Europe (one in Netherlands, one in Greece and nine in the UK). Embodied emissions from these systems range between 1902 and 13 378 t CO\textsubscript{2}ek m\textsuperscript{−1} (National Rail 2009, International Union of Railways 2016). The UK intercity rail with the highest number of emissions contains 10% tunnel (National Rail 2009), while the case studies in Greece and The Netherlands had no tunnels (International Union of Railways 2016). The UK Bothnia freight rail was the only freight rail case study with a reported 2671 t CO\textsubscript{2}ek m\textsuperscript{−1} embodied emissions (International Union of Railways 2016). Seven light rail case studies were reviewed and their emissions range from 47 to 8475 t CO\textsubscript{2}ek m\textsuperscript{−1} (Chester et al 2012, 2013, Lederer et al 2016). The Tokyo light rail line is the extrema (maximum) in the light rail boxplot diagram (see figure 4) with 11% tunnels. Three Metro rail case studies were reviewed in this study and they were in the UK (12 712 t CO\textsubscript{2}ek m\textsuperscript{−1}), Canada (30 445 t CO\textsubscript{2}ek m\textsuperscript{−1}) and Asia (4984 t CO\textsubscript{2}ek m\textsuperscript{−1}). The Metro rail embodied GHG emissions had the largest variation. The LCA method adopted in studying the emissions associated with the case studies are different. While the Sheppard subway line was studied with pseudo LCA method, Shangai Metro was analyzed with a process based LCA method (Li et al 2016, Saxe et al 2017) and Crossrail with the hybrid LCA method (Paris and de Silva 2010). Embodied emissions associated with the HRT range from 0.5 to 6 t CO\textsubscript{2}ek m\textsuperscript{−1} (Chester and Horvath 2010).

The published GHG intensity of rail infrastructure varies significantly across the literature, leaving a question as to how these numbers can be used to help estimate the GHG of future projects. In general metro rail has the highest emissions, and light rail systems the lowest (of the types with multiple studies), however the quantity of case studies per rail type is highly uneven, making it hard to draw conclusions or comparisons. Section 5.1 below converts the GHG emission per kilometre to an equivalent at-grade construction to account for variation in material need between at-grade, elevated and tunnelled rail infrastructure.

### Table 5. Payback period of case studies.

| Author                        | Payback period (Years) |
|-------------------------------|------------------------|
| Lave (1978)                   | 535\textsuperscript{a} |
| Chester and Horvath (2010)    | 6–8 at high occupancy, 28–71 at mid-level occupancy\textsuperscript{b} |
| Paris and de Silva (2010)     | 5–32                   |
| Chang and Kendall (2011)      | 13                     |
| Chester et al (2012)          | 10 years after operation |
| Chester et al (2013)          | 30–60 years after operation |
| International Union of Railways (2016) | 9           |
| International Union of Railways (2016) | 12           |
| Chester and Cano (2016)       | 14 years after operation |
| International Union of Railways (2016) | 15           |
| Saxe et al (2017)             | 9–35 years after operation |

\textsuperscript{a} Outlier base on energy use for mobility in a different era.
\textsuperscript{b} Different scenarios based on occupancy.

5.1. Payback period

Payback period, the time required to save—through travel behaviour and land use change—as much GHG as were invested in construction, is measured in decades across the case studies. Nine out of 22 publications included payback periods in their study as summarized in table 5. The payback periods are influenced by the total emissions associated with the rail system including its embodied emissions, operating and maintenance needs, travel behavior and land use outcomes (Chester and Horvath 2010, Saxe et al 2017). Published payback periods range from 5 to 535 years with Lave (1978) the extreme outlier and base on energy use for mobility in a different era. While outside the post 2009 window of analysis, we include Lave as the first paper to analyze payback period. Three payback scenarios were analyzed by calculating the mean of the observation and using the average, the minimum, and the maximum values of the payback scenarios were analyzed by calculating the mean of the observation and using the average, the minimum, and the maximum values of the payback years for typical, optimistic, and pessimistic scenarios, respectively. The typical payback period (with Lave excluded) is 20 years, the optimistic scenario is 15 years, and the payback period for the pessimistic scenario is 27 years.

The decades long reported payback periods and the impetus to reduce GHG emissions in the short term indicate the significant efforts are needed to carefully reduce the embodied GHG of new rail infrastructure (while simultaneously fully taking advantage of the infrastructure for travel behavior and land use change).

When considering the payback period of these 10 cases, there is an uncertainty up to 75%. The contribution of the embodied emissions to this uncertainty is up to 30%; the rest, 45%, is due to operational
emissions and assumptions such as the estimation of the ridership. The estimation of the embodied emissions is based on the construction period and therefore static in time and not affected by dynamic factors which change over the years such as travel behaviour or railcar technology. As such the uncertainty in the upfront embodied emissions should be reducible with more detailed data collection and reporting.

With increasing pressure and urgency to reduce global GHG emissions and the associated impacts of climate change, GHG payback periods measured in decades may become unacceptable. As the cost half of the equation, the embodied emission of rail infrastructure will need to reduce to facilitate faster payback periods.

6. A generalized model of GHG emissions per kilometre of rail infrastructure

The wide heterogeneity in rail projects, type, location, design, soil characteristics leads to a large range of embodied GHG in assessed projects. This is amplified by the variations in scope, boundaries, approaches and goals in the published research. This heterogeneity is the key challenge in developing a generalized model for estimating the embodied GHG emissions in rail infrastructure projects.

To develop a sketch model of embodied GHG in rail, the first step was to track the relationship between the embodied GHG emissions and the length of the rail infrastructure. To examine this relationship, a linear modeling approach has been adopted. The reason for choosing this approach is that ‘at heart, LCA is a tool based on linear modeling’ (Guinée et al 2001). Linear regression is adopted for testing the impact of at-grade, elevated and tunnelled construction on embodied GHG emissions in line with past findings that type of construction in a major driver of overall embodied GHG (Chester 2008, National Rail 2009, Chang and Kendall 2011).

Any model has some limitations which increases its uncertainty. Uncertainty in statistical analyses arises from random factors and is quantified based on the standard deviation of the measured quantities (Field 2013). In this framework, the statistical analysis of this study scopes out the effect of the detailed design factors affecting the embodied emissions of rail infrastructure including its function, geometry, specifications, emphasis on whole lifecycle, legislative constraints and socio-economic factors. This comes as a result of approaching the subject macroscopically, due to missing data and construction details. The embodied emissions are affected by the aforementioned factors which are not explicitly examined in the statistical analysis used in this paper.

Using the reviewed case studies, we developed a sketch model of the GHG emissions per kilometre of rail infrastructure. This analysis was performed using inferential statistics. Analyses were conducted with IBM SPSS software. It is common practice to normalize the GHG emissions per infrastructure length in kilometre as discussed above (and done above in figure 4); this obscures the large differences in material and energy needs to construct at-grade, elevated or tunnelled rail infrastructure. Previous research has identified tunneling as 3–89 times more GHG intensive than at-grade (National Rail 2009, Chang and Kendall 2011, Westin and Kågeson 2012, Miyoshi and Givoni 2014, Dimoula et al 2016, Hanson et al 2016, International Union of Railways 2016, Li et al 2016, Bueno et al 2017). Below we convert the GHG findings in the reviewed paper to at-grade kilometre equivalents, meaning we apply a scale factor to the case studies to convert to equivalent at-grade distances based on the ratio of GHG emissions between at-grade, elevated and tunnelled construction in the reviewed papers. Most of the papers (National Rail 2009, Chang and Kendall 2011, Westin and Kågeson 2012, Miyoshi and Givoni 2014, Dimoula et al 2016, Hanson et al 2016, International Union of Railways 2016, Li et al 2016, Bueno et al 2017) clearly identify the tunneling percentage of the total rail line constructed. Some (Infraestructuras 2015, Yue et al 2015, Chester and Cano 2016, Dimoula et al 2016, Hanson et al 2016, International Union of Railways 2016) provided information about the bridges/elevated sections. With two exceptions (except (Hanson et al 2016 Chang and Kendall 2011), the papers consider stations but generally without providing detailed design and dimension data. As such, the stations could not be considered as separated variables during this process. Accordingly, stations were assumed to be at-grade, elevated or underground in parallel to the construction type for the attached section of rail line. More specifically, we assume that that the embodied GHG of stations is proportional to the length and type of constructed rail. A similar approach was adopted in previous efforts to assess the GHG impact of different types of rail infrastructure by National Rail (2009). This assumption ignores differences in stations spacing and station design and with more detailed data in future publications it would be better to model stations separately. Some of the cases were excluded as they did not provide details on the tunnelled/elevated/at-grade portions (Lave 1978, International Union of Railways 2016). From a total of 57 case studies, 44 were used in this part of the analysis. In publications with more than one scenarios for the same case (National Rail 2009, Yue et al 2015), the most GHG intensive scenario was used. A multivariate analysis was applied. The analysis showed that the length of tunneling (p-value = 0.000) and the length of at-grade (p-value = 0.000) affected the embodied GHG emissions to a significant level. The length of elevated section was not found to affect embodied GHG to a statistically significant level (p-value = 0.764). Linear regression was used to identify the relative GHG intensity of
tunnelled length compared to at-grade construction. The linear regression lead to the following:

\[
y = (18759 \pm 3169)x_1 + (685 \pm 469)x_2 + (233997 \pm 35561)
\]

\(y\) is the tonnes of embodied GHG emissions
\(x_1\) is the kilometres of tunneling
\(x_2\) is the kilometres of at-grade.

The embodied emission generation of tunneling is 27 ± 5 times more than at-grade construction, and explains 46.8% of the variance in GHG emissions between case studies. We converted the data by adjusting values measured on different scales, at-grade and tunneling construction, to a notionally common scale, that is at-grade equivalents. The factor that was applied to convert tunnelled lengths to at-grade was 27.

For elevated sections, we reran the regression including only the eight case studies that had more than 10% elevated length (Infraestructuras 2015, Yue et al 2015, International Union of Railways 2016), finding that elevated structures had embodied GHG 6 ± 1 times more than at-grade, explaining 16.7% of the variance. The linear regression analysis for the elevated sections was applied for comparison reasons but not for further use, since the length of elevated section was not found to affect embodied GHG to a statistically significant level (p-value = 0.764), and given the low number of case studies with relevant data is not included in the transformed to at-grade equivalents in figure 5 below.

An analysis of variance (ANOVA) demonstrated that the embodied GHG emission generation is differentiated depending on the types of rail infrastructure. In other words, there is a significant difference in the results between the different types of rail. Thus, a linear regression analysis was applied within each type of rail infrastructure that had a sufficient number of cases for the analysis to be conducted (HSR, light rail, commuter rail, intercity rail). The number of publications per rail type is provided to illustrate the bias of the results. For commuter rail based on two publications and 6 case studies, tunneling affects the embodied emission generation 37 times more than at-grade, explaining 99.8% of the data variance. For HSR rail based on 11 publications and 25 case studies, tunneling affects the embodied emission generation 37 times more than at-grade, explaining 48.7% of the data variance. For intercity rail based on three publications and 11 case studies, tunneling affects the embodied emission generation 8 times more than at-grade construction, explaining 54.6% of the variance. For light rail based on five publications and 7 case studies, tunneling affects the embodied emission generation 3 times more than at-grade construction, explaining 54.2% of the data variance. The range of tunneling impact may be an artifact of the quality of the data, since every case was unique. So, to facilitate comparison between rail types and case studies, the average tunneling effect ratio equal to 27 was used to convert the reported GHG emissions in the reviewed papers to equivalent at-grade impacts. Figure 5 illustrates the at-grade adjusted embodied emissions reported in the reviewed literature, categorized by rail infrastructure type. The converted equivalent at-grade kilometre is denoted as ‘n_km’.

There is significant unreduced heterogeneity in the results. Details of methodology, assumptions, system boundaries and data collection techniques should be taken into consideration when interpreting the outcome of these analyses.

Overall, the adjusted boxplot shows a reduced range for embodied GHG emissions categorized per
type of rail, however significant variation remains. The large variation in the embodied GHG emissions is partly a result of different demands of supporting infrastructures (bridges) in the rail system not controlled for in the adjustment. The Tokyo light rail line, with the highest embodied emissions, is 11% tunnels (Morita et al 2013) and is the only extrema in the box-plot diagram.

The data reviewed demonstrated a significant level of irreducible uncertainty in the body of knowledge given wide variations in approach, data quality and boundaries. Taking as a starting point the linear normalization process, it is possible to develop a model by using the length of tunneling and of at-grade construction as input (independent variables) and the GHG emissions as output (dependant variable). We explored which of the models provided by IBM SPSS software best described the relationship between the converted at-length length of rail infrastructure and the generated embodied GHG emissions. The models considered for the interpretation of the results are presented in table 6.

The larger the $R^2$ value, the larger the data variance explained by the model. As illustrated in the table 6, the model that best describes the relationship is the cubic model followed by the linear and the quadratic model. The rest of the models with high significance ($p = 0.000$) have a smaller $R^2$. Nevertheless, the cubic model is prone to adjusting to non-homogenous samples like the present one. As a result, the cubic model was not monotonically increasing. It demonstrated that at some points in the curve the embodied GHG emissions were decreasing as the length of the rail infrastructure was increasing, something that does not occur in reality. Therefore, the linear function was considered to be the most appropriate for the development of a sketch model in line with the linear nature of the LCA method. The sensitivity of the model suggests its revision with more case studies as more are published in the future.

The choice of using the distance data (length of rail) for developing a model was based on the significant effect ($p$-value $= 0.000$) of the at-grade and tunneled distance. This generates a model that can be used in cases where other data are missing or are limited. For example, as discussed above, during the scoping process for a rail project, detailed design data on material type, use and quantity are unavailable. In cases where detailed data are available, project specific GHG assessment should be carried out based on the physical design of the project to be analyzed. In future research, it will be valuable to create a model based on more specific rail design parameters (e.g. soil type, construction approach, local construction traditions). Given the detail and quality available in the reviewed papers, this was outside the scope of this paper.

The next step was to calibrate the model in order to adjust to the reviewed data. Since this paper targets a sketch model appropriate for most projects, the case studies which were proportionally far from the linear model were removed as outliers: Li et al (2016), National Rail (2009) NLP-SBC Total case, Westin and Kågeson (2012), Yue et al (2015) A5 case, Chang and Kendall (2011), Bueno et al (2017). The inclusion of these outliers would artificially move the mean to a less representative point (Field 2013). After removing the outlier cases, the IBM SPSS software generated an updated model which explained the 77% of the data variance, compared to the 45.4% the data variance explained by the initial model. The linear model is:

$$Y = b_0 + b_1 \cdot x$$

where $Y$ is the dependent variable (GHG emission in kg), $x$ the at-grade distance and $b_0, b_1$ the model coefficients.

The adjusted $R^2$ value for the linear model is 0.454, which explains 45.4% of the data variance. This indicates that the linear model is a good fit for the data. The model coefficients are $b_0 = 3.034 \times 10^7$ and $b_1 = 6.697 \times 10^3$.

The quadratic model, which includes a squared term, is also a good fit for the data, with an adjusted $R^2$ value of 0.494. The quadratic model is:

$$Y = b_0 + b_1 \cdot x + b_2 \cdot x^2$$

where $b_2$ is the coefficient of the squared term. The coefficients for the quadratic model are $b_0 = 2.669 \times 10^7$, $b_1 = 7.232 \times 10^3$, and $b_2 = -6.433$.

The cubic model, which includes a cubic term, is the best fit for the data, with an adjusted $R^2$ value of 0.550. The cubic model is:

$$Y = b_0 + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3$$

The coefficients for the cubic model are $b_0 = 6.365 \times 10^7$, $b_1 = 1.948$, $b_2 = -3.435$, and $b_3 = 0.001$.

The logistic model, which is a S-shaped curve, is also a good fit for the data, with an adjusted $R^2$ value of 0.233. The logistic model is:

$$Y = \frac{b_0}{1 + e^{-b_1 \cdot x}}$$

The coefficients for the logistic model are $b_0 = 7.6 \times 10^7$ and $b_1 = 0.001$.

The models were compared using the $R^2$ value, the significance of the coefficients ($p$-value), and the coefficient of determination ($R^2$). The model that best describes the relationship is the cubic model followed by the linear and the quadratic model. The rest of the models with high significance ($p = 0.000$) have a smaller $R^2$. Nevertheless, the cubic model is prone to adjusting to non-homogenous samples like the present one. As a result, the cubic model was not monotonically increasing. It demonstrated that at some points in the curve the embodied GHG emissions were decreasing as the length of the rail infrastructure was increasing, something that does not occur in reality. Therefore, the linear function was considered to be the most appropriate for the development of a sketch model in line with the linear nature of the LCA method. The sensitivity of the model suggests its revision with more case studies as more are published in the future.

The choice of using the distance data (length of rail) for developing a model was based on the significant effect ($p$-value $= 0.000$) of the at-grade and tunneled distance. This generates a model that can be used in cases where other data are missing or are limited. For example, as discussed above, during the scoping process for a rail project, detailed design data on material type, use and quantity are unavailable. In cases where detailed data are available, project specific GHG assessment should be carried out based on the physical design of the project to be analyzed. In future research, it will be valuable to create a model based on more specific rail design parameters (e.g. soil type, construction approach, local construction traditions). Given the detail and quality available in the reviewed papers, this was outside the scope of this paper.

The next step was to calibrate the model in order to adjust to the reviewed data. Since this paper targets a sketch model appropriate for most projects, the case studies which were proportionally far from the linear model were removed as outliers: Li et al (2016), National Rail (2009) NLP-SBC Total case, Westin and Kågeson (2012), Yue et al (2015) A5 case, Chang and Kendall (2011), Bueno et al (2017). The inclusion of these outliers would artificially move the mean to a less representative point (Field 2013). After removing the outlier cases, the IBM SPSS software generated an updated model which explained the 77% of the data variance, compared to the 45.4% the data variance explained by the initial model. The linear model is:

$$Y = b_0 + b_1 \cdot x$$

where $Y$ is the dependent variable (GHG emission in kg), $x$ the at-grade distance and $b_0, b_1$ the model coefficients.

The adjusted $R^2$ value for the linear model is 0.454, which explains 45.4% of the data variance. This indicates that the linear model is a good fit for the data. The model coefficients are $b_0 = 3.034 \times 10^7$ and $b_1 = 6.697 \times 10^3$.

The quadratic model, which includes a squared term, is also a good fit for the data, with an adjusted $R^2$ value of 0.494. The quadratic model is:

$$Y = b_0 + b_1 \cdot x + b_2 \cdot x^2$$

where $b_2$ is the coefficient of the squared term. The coefficients for the quadratic model are $b_0 = 2.669 \times 10^7$, $b_1 = 7.232 \times 10^3$, and $b_2 = -6.433$.

The cubic model, which includes a cubic term, is the best fit for the data, with an adjusted $R^2$ value of 0.550. The cubic model is:

$$Y = b_0 + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3$$

The coefficients for the cubic model are $b_0 = 6.365 \times 10^7$, $b_1 = 1.948$, $b_2 = -3.435$, and $b_3 = 0.001$.

The logistic model, which is a S-shaped curve, is also a good fit for the data, with an adjusted $R^2$ value of 0.233. The logistic model is:

$$Y = \frac{b_0}{1 + e^{-b_1 \cdot x}}$$

The coefficients for the logistic model are $b_0 = 7.6 \times 10^7$ and $b_1 = 0.001$.
Finally, the impact of construction stage revealed that the reported GHG emission from the proposed projects (1928 ± 487 per at-grade kilometre) are higher that the constructed projects (941 ± 270 per at-grade kilometre). Since one objective of this paper is to summarize the published literature in tables of values that could support preliminary planning estimates of embodied emissions, table 8 summarizes estimates for emissions for the different infrastructure categories.

There is a lack of information on three significant features of the LCA: reliable data, characterization factors and LCA modelling methods (Passer et al 2015). Recovering this shortage of reliable data and characterization factors is beyond the scope of the present study. However, the authors explored the development of a modelling method using the existing data. This process was challenging as LCA is, by nature, a multi-model multi-paradigm approach (Guinée et al 2018, Yang and Heijungs 2018) and the necessary assumptions (e.g. GHG intensity of materials, accuracy of construction documents as predictive of material use) are very difficult to confirm (Guinée et al 2018).

7. Conclusions

A literature review of published papers dealing with the embodied GHG impacts of rail infrastructure identified 22 relevant papers with 57 case studies. The publications were classified based on their research goals, LCA methods, system boundaries, functional units, embodied GHG emissions, and GHG payback periods. While there has been an increasing body of literature that includes assessment of the GHG intensity of rail infrastructure, most have completed embodied GHG assessment as a step towards another goal rather than the main focus of the paper. Overall, the range of approaches, boundaries, functional units and methods are wide with un reducible heterogeneity in the reviewed case studies.

Large variation in scope, functional unit, boundaries and inventory methods make it challenging to compare the case studies directly. All the case studies include analysis of the GHG impact of construction but to varying degrees and with different boundaries. Data sources similarly vary across case studies. An ANOVA demonstrated that the embodied GHG emission generation is differentiated depending on the types of rail infrastructure. In other words, there is a

Table 7. Mean of the embodied GHG emissions (tCO2e) per kilometre of at-grade with their standard error.

| Type of rail | Number of cases | Mean of the embodied GHG emissions (tCO2e) | Standard error |
|-------------|-----------------|---------------------------------|--------------|
| Commuter    | 6               | 2585                            | 896          |
| Freight     | 1               | 650                             |              |
| HRT         | 4               | 2                               | 1            |
| HSR         | 25              | 1018                            | 224          |
| Intercity   | 11              | 1929                            | 320          |
| Light Rail  | 7               | 422                             | 296          |
| Metro       | 3               | 4670                            | 4026         |
| Total       | 57              | 1400                            | 268          |

\[ y' = 935 \cdot x + 23205 \] (where \( y' \): GHG emissions in tCO2e and \( x \): the equivalent at-grade kilometre of rail lines). However, following the reasoning of the characterization factors that multiplies the subject of interest to a coefficient without adding a constant, a linear model was developed without the constant (23205). The resulting model is \( y = 941 \cdot x \) and explains the 77.23% of the data variance. The resulting model suggests that 941 tCO2e are generated per at-grade kilometre. A closer look to the numbers reveals that the coefficient of the resulting model is actually the mean of the cases considered. This suggests that the calculation of the means of the case studies is a sufficient indicator for linear modelling development. For comparison reasons, the mean of all the 57 cases, which includes the outlier cases, is \( 1400 \pm 268 \) tCO2ekm\(^{-1}\) of at-grade built. The means of the different types of rail infrastructure are provided in table 7.

Given the small number of case studies per rail type (e.g. HSR, Metro rail) all the 57 cases were considered as one category in the initial model. We additionally tested the predictive power of case study location, LCA methods and construction stage. An ANOVA showed that the specific location of the case study did not play a significant role on the embodied GHG emission calculation. However, in general, the case studies from Europe employed more tunneling and have a higher calculated embodied GHG emission per kilometre. The impact of LCA approach was also tested. Prior to exploring the methodology effect, the hybrid method was excluded from the analysis due its high uncertainty (1444 ± 1409 tCO2e per at-grade kilometre). The parametric method was also removed as it was used in only one publication. Methodology was found to have a significant effect on the number of embodied GHG emissions reported with process-based LCA reporting generally lower embodied GHG emissions (582 ± 155 per at-grade built kilometre) when compared to both the pseudo (2709 ± 759 per at-grade built kilometre) and the simplified methods (1678 ± 240 per at-grade built kilometre). This is in line with bottom up LCA processes generally producing lower bound assessments.
significant difference in the results between the different types of rail. In general, metro rail had the largest embodied GHG emissions, followed by intercity rail, high speed rail and light rail. However, this must be considered in context of the varying number of case studies per rail type and the general importance of infrastructure type (e.g. tunnelled or elevated) to embodied GHG across rail types. Embodied GHG emissions normalization per distance highlights the influence of tunnels and bridges on embodied GHG emissions.

The papers dealing with embodied GHG emissions have originated in 11 countries, 10 of which are in the global north, future research from the global south would benefit the robustness of the field. Process based attributional LCA is the most common analysis approach, though some researchers have employed pseudo LCA, hybrid LCA and parametric approaches. The published payback period varied, ranging between 5 and 535 years, with 20 years as a typical average payback period. The biggest challenges to comparing and combing the findings were (1) inconsistent boundary selection between papers and (2) limited communication of the infrastructure details and embodied GHG calculations in many papers. As such, the papers make a start towards a baseline of embodied GHG emission for rail infrastructure but more standardization and detailed communication of construction material and fuel use is needed. A key contribution of this paper is identification of the need for future standardization in embodied GHG assessment and agreement on standards for communicating background data. Future research in this area should provide clear descriptions of (1) the kilometres of tunnelled, elevated, and at-grade construction included in the case study, (2) the range of ground conditions and elevations, (3) boundaries of assessment (specific communication of the embodied emission in each studied element (track beds, tunnels, elevated sections/bridges and stations) to allow for comparability between studies), (4) a description of all stations. The field will further benefit from a consideration of appropriate functional units for rail infrastructure. The current common functional units, PKT and kilometre, have limitations in regard to the heterogeneity of ground conditions, construction types, and passenger capacity of otherwise similar rail lines. A consideration of the linearity assumption is also needed.

Despite the heterogeneity in reviewed papers, it was possible to develop a range of findings. An ANOVA showed that the specific regional location of the case study did not play a significant role in the embodied GHG emissions calculation, however areas that required more tunnelling or more elevated structures due to topography led to more GHG emissions. LCA methodology was found to have a significant effect on the quantity of embodied GHG emissions reported, with process-based LCA reporting generally lower embodied GHG emissions, this is in line with bottom up approaches generally providing lower bound assessments. Finally, the stage of project development at which the GHG assessment was carried out was found to have a significant effect on the quantity of assessed embodied GHG emissions, with the reported GHG emissions from proposed projects higher than constructed projects. This finding requires more investigation. We hypothesize that this could be a function of data quality and access. The size effect of these methodological effects should be taken into consideration when comparing case studies within this review or in the rail infrastructure embodied GHG literature more broadly.

The present paper introduced a novel conversion methodology, transforming the assessed embodied GHG emissions to equivalent and at-grade kilometres. This conversion permitted the development of a linear model for estimating GHG emissions. The statistical model finds that overall 941 ± 168 tCO₂e are embodied per kilometre of rail at-grade, while tunneling has 27 ± 5 times more embodied GHG per kilometre than at-grade construction. This simple distance-based statistical model can be used in cases where other data are missing or are limited as a rough estimate of potential embodied GHG. This model provides a first step towards a generalized approach to rail infrastructure embodied GHG assessment based on existing literature for project scoping. This cannot and should not replace detailed case-specific GHG assessment as design progresses and project specific details become available.

The statistical model is based on the findings of published literature and does not explicitly consider function, geometry, specifications, emphasis on whole lifecycle, legislative constraints, socio-economic factors, or the physical and environmental conditions of the construction site. More research is needed to create robust formulas for generalized embodied GHG assessment of rail projects. As more papers are published in the field, the data summarized here, and the approach to at-grade conversion, can be used to update the sketch model for embodied GHG per kilometre in this paper. As the field moves forward, clear communication of boundaries and data will be necessary to advance beyond the limitations identified in this paper.

Acknowledgments

The authors gratefully acknowledge the University of Toronto and the financial support of our research partners. Nikolaos Kalviotis’ contributions to this paper were supported by Metrolinx Crown Agency. Olubanjo Olugbenga’s contributions to this paper were supported by Arup and the Ontario Centers of Excellence. The authors thank the anonymous reviews
and editors for the review comments and their improvements to this paper. Any data that support the findings of this study are included within the article.

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