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DOI:
10.1016/j.trd.2015.10.021

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Krezo, S, Mirza, O, He, Y, Makim, P & Kaewunruen, S 2016, 'Field Investigation and Parametric Study of Greenhouse Gas Emission from Railway Plain-Line Renewals', *Transportation Research Part D: Transport and Environment*, vol. 42, pp. 77-90. https://doi.org/10.1016/j.trd.2015.10.021

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REVISED TECHNICAL PAPER

"Field Investigation and Parametric Study of Greenhouse Gas Emission from Railway Plain-Line Renewals"

(Title contains 13 words)

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Manuscript Summary:

Total pages	30 (including 1-page cover)
Number of figures	4
Number of tables	6

Field Investigation and Parametric Study of Greenhouse Gas Emission from Railway Plain-Line Renewals.

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Abstract

Railway transportation is becoming increasingly important in many parts of the world for mass transport of passengers and freight. This study was prompted by the industry's need to systemically estimate greenhouse gas emissions from railway construction and maintenance activities. In this paper, the emphasis is placed on plain-line railway maintenance and renewal projects. The objective of this study was to reduce the uncertainties and assumptions of previous studies based on ballasted track maintenance and renewal projects. A field-based data collection was carried out on plain-line ballasted track renewals. The results reveal that the emissions from the materials contribute more than nine times the CO_2-e emissions than the machines used in the renewal projects. The results show that extending the lifespan of rail infrastructure assets through maintenance is beneficial in terms of reducing CO_2-e emissions. Analysis was then carried out using the field data. Then the results were compared to two ballastless track alternatives. The results show that CO_2-e emissions per metre from ballasted track were the least overall, however, the maintenance CO_2-e emissions are greater than those of ballastless tracks over the infrastructure lifespan, with ballasted track maintenance emitting more CO_2-e emissions at the 30 and 60 year intervals and the end of life when compared to the ballastless track types. The outcome of the study can provide decision makers, construction schedulers, environmental planners and project planners

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with reasonably accurate GHG emission estimates that can be used to plan, forecast and reduce emissions for plain-line renewal projects.

Keywords: railway maintenance, track beds, greenhouse gas emissions, random, uncertainty.

Nomenclature

C_i	energy content factor of type i fuel (GJ/kL).
CO_2-e	carbon dioxide and equivalents, including CO_2, CH_4, N_2O and synthetic gases.
E_{CM}	CO_2-e emission per unit track length for construction machinery (kg/m).
EF_k	the embodied emissions factor for type k material (kg/kg).
E_{IC}	CO_2-e emissions per unit of track length for the initial construction (kg/m).
E_{ij}	amount of emission of gas species j relating to fuel i (kg).
E_l	CO_2-e emission per unit track length per year of lifespan (kg/m.year).
E_m	CO_2-e emission due to maintenance per unit track length (kg/m).
EM	embodied CO_2-e emissions per unit track length (kg/m).
EM_{ic}	CO_2-e emission per unit track length for materials used in initial construction (kg/m).
EM_r	CO_2-e emission per unit track length for materials used in renewals and maintenance activities (kg/m).
E_u	CO_2-e emission per metre of track from ballasted track maintenance activities (kg/m).
F_{ij}	emission factor for gas j by fuel i (kg/GJ).
L	lifespan, or the time period of construction and operation phases of the lifecycle (year).
M	types of maintenance activities.
MF	maintenance frequency.
N	total number of material types used in track construction.
Q_i	quantity of type i fuel -(kL).
QM_k	quantity of material k required per meter of track construction (kg/m).

T	track length processed in a renewal maintenance project (m).

Subscript

i, *j*, *k*	fuel, gas species and material indices
n	maintenance activity index

1 Introduction

Rail transportation is becoming ever more attractive especially in Europe, Japan and Asia. In Australia, the railway infrastructure is built to carry either passengers or freight, or both, uni- and bi-directionally (Remennikov and Kaewunruen, 2014), and the nation's heavy haul rail network is one of the world's best and most efficient transport systems (Kaewunruen and Remennikov, 2010). The railway track (also called 'railroad' in the US) is a complex system built upon many supporting elements within the track corridors. The operational and logistic point of view adds another layer of the complexity. Railway infrastructure is constructed to have a design life ranging from 10 years to 100 years, depending on construction type (ballasted or ballastless), construction materials, loading and weathering conditions. Throughout this period, maintenance and renewals of aged components are required to assure the safety and reliability of the rail network for passengers and cargo (Remennikov and Kaewunruen, 2008; Kaewunruen et al., 2015).

In general, there are two types of railway infrastructure: ballasted and ballastless tracks. Ballasted track is laid on crushed aggregates and capping layers that are placed on the formation, with the combination commonly referred to as the 'substructure'. It supports a combination of sleepers, rails and fixings which is commonly referred to as the 'superstructure' (Manalo et al., 2010; Burrow et al., 2007). Ballastless track uses a concrete slab system and special fixings to support the steel rails which transfer the loads from passing trains to the concrete slab. Michas (2012) explains that ballastless track is superior to ballasted track due to its higher stability, less frequent maintenance, reduced height and longer lifecycle. The disadvantages of ballastless track are inflexibility and higher initial construction costs due to the increased concrete and steel content.

Ballasted track has been used since the early 1800’s and is still very common but the popularity of ballastless track has increased over the last 40 years (Michas, 2012).

In recent decades, the issue of greenhouse gas (GHG) emissions in railway systems has attracted much attention in response to the concern created by climate change (Schwarz, 2009). The impact of railway systems on the global environment is becoming a more and more important part of their life cycle analysis (Chester and Horvath, 2009). Inevitably, the decision on the choice of track type in railway construction projects will depend on the outcome of greenhouse gas emission analysis as well as on social, economic and other environmental considerations. This has prompted investigations into the GHG emissions from the construction and maintenance of track beds (Kiani et al., 2008; Milford and Allwood, 2010; Chang and Kendall, 2011; Schwarz, 2009; Chester and Horvath, 2011; Ueda et al., 2008).

The planning and design are the first steps in developing a railway system. Some major considerations include construction type, track characteristics, routes and intended use. Construction follows and with the assistance of diesel engine driven machines, a reduced timeframe can be achieved. Once construction of the railway is complete, the railway becomes operational. Maintenance is then carried out for the railway’s lifespan as it is crucial to ensure the track system operates successfully. Maintenance and renewal of ballasted track bed includes ballast resurfacing (ballast tamping, regulating and stabilising), rail grinding, ballast cleaning, continuous track renewals and switch renewals, with all these activities relying on diesel engine driven machines to reduce the timeframe and increase the scope of maintenance. The end of life activities include the demolition and recycling of materials. An illustration of the railway system and inclusions of the current study are shown in Figure 1a.

The findings of the literature review show that some of the previous studies had relied on machinery assumptions which were not verified. Some of the assumptions were believed to have led to the greatest case scenario in GHG emissions estimating.

This study has been conducted with the objective to reduce the uncertainties and assumptions of previous studies by carrying out a field based data collection of railway maintenance and renewal activities and report on the CO_2-e activities from railway maintenance. The objective of the parametric study is to estimate the CO_2-e emissions from the maintenance of ballasted and ballastless track, by providing a comparison in a unit length of measurement. The results are then used to estimate CO_2-e emissions from railway maintenance in emissions forecasting. The outcome of the study can provide decision makers, construction schedulers and project planners with reasonably accurate GHG emission estimates that can be used to plan, forecast and reduce emissions for plain-line renewal projects.

2 Greenhouse Gas Emissions and Life Cycle of Plain-line Railway

2.1 Maintenance and Life Cycle of Plain-line Railway

In Australia, the most commonly used type of track form is ballasted track. Ballasted track is preferred due to the low initial cost, ease of renewal and maintenance, and the availability of materials (Kaewunruen et al., 2011a, 2011b, 2014). Esveld (2003) suggests that, while ballastless track is more expensive to construct, its reduced long-term maintenance is a desirable characteristic for train lines with limited maintenance possession times. Rheda (2000) also claims that ballastless track systems are capable of carrying increased axle loads, operation at faster speeds, require little track bed maintenance and have an increased service life.

Track replacement occurs as a periodic maintenance activity. Ballasted track (with concrete sleepers) is designed to last 10 to 100 years (Kaewunruen and Remennikov, 2008); however, increased rail traffic, poor maintenance practices and material degradation can result in reduced life of the track. Alternatively, high quality initial construction, efficient and frequent maintenance and low traffic loads can result in an increased lifespan.

Ballasted track resurfacing is the process of removing voids from aggregates in the track bed. It comprises of three activities: tamping, regulating and stabilising which occur in ballasted track only. Tamping corrects track geometry by packing the aggregates whilst lifting and lining the track; ballast regulating returns the aggregates and reinstates shoulder widths; and stabilising compacts the aggregates to ensure uniformity and compaction in the ballast region.

Rail head grinding and rail replacement are also important maintenance activities. Rail head grinding is a corrective maintenance activity that removes surface corrosion and cracking from the rail head and restores the rail profile. Studies on rail head grinding have found that the life of the rail can be extended by routinely undertaking this activity. Rail lines without regular grinding have a higher risk of rail breakage (Podofillini et al., 2006). Rail replacement is required when the rail is worn down to an unacceptable depth. Typical steel rail sections are expected to last in excess of 45 years in Europe or sometimes over 75 years in Australia, depending on loading and site conditions (Girsch et al., 2008; Kaewunruen et al., 2014; 2015). Increased rail deterioration is caused by tight curve radii's, increased traffic loads and lack of maintenance (Correa et al., 2011).

Ballastless track systems are widely available and, as Michas (2012), explained there are 34 varieties of ballastless track bed which vary in design and are constructed to suit different topography and technological factors. For the purpose of a parametric study, the results from Kiani et al. (2008) have been chosen to compare the ballasted track bed and ballastless track systems and show the impact of track bed choice on future maintenance CO_2-e emissions.

2.2 Research on Greenhouse Gas Emissions

Greenhouse gas is a collection of gases that produce a greenhouse effect in the atmosphere. These gases include CO_2, CH_4, N_2O, HFCs, SF_6, CF_4 and C_2F_6. They are denoted as CO_2-e, which is defined by DOE (2014) as carbon dioxide equivalent.

The transportation sector globally is responsible for 13 % of total CO_2-e emissions, (Rao 2009). The importance of investigating the environmental impact of track bed selection has increased, with decision makers and planners required to assess many factors when selecting track construction type. The maintenance of the railway is vital in ensuring the reliability and longevity of the infrastructure and needs to be considered in lifecycle studies.

Remennikov and Kaewunruen (2008) explained that components in plain-line tracks experience considerably less wear and tear or damage when compared with special track components, such as turnouts, diamonds or crossovers. However, plain-line railway track components deteriorate faster in tight curves, under heavy axle loads and in adverse weather conditions. Hence more frequent maintenance is required for such sections and conditions (Lewis and Olofsson, 2004).

A critical literature review was carried out on the maintenance and construction activities of ballasted and ballastless track beds in this study. A study by Milford and Allwood (2010) assessed the current and future impacts of track bed types in the UK rail network. The authors found that in the UK, maintenance and replacement of rail components emitted between 430 and 934 thousand tonnes of CO_2 annually for 33,500 kilometres of railway track. The biggest contribution to CO_2 emissions was from steel rail manufacture (it is noted that the study only considered carbon dioxide emissions). Since the steel rail component of a railway track system was the highest contributor to GHG emissions, the authors investigated future track designs of quadruple and double headed rail, with the findings showing that GHG emissions could be reduced by 40 % if the rail could be reused instead of replaced. Whilst the study considered the whole lifecycle, the maintenance CO_2 emissions reporting was difficult as there was no published literature at the time, therefore, estimates were used for machinery fuel consumption, renewal and maintenance frequencies, construction speeds and maintenance data.

Swartz (2009) reported on the environmental impact of high speed rail construction in Europe. The author found that the track bed selection and the share of bridges and tunnels have the greatest impact on the overall CO_2-e emissions. The study by Swartz (2009) primarily concentrated on the construction and the operation of track infrastructure.

Lee et al. (2008) investigated the lifecycle of ballasted and ballastless slab track with a focus on sustainable track construction. The authors found that ballasted track had a higher energy consumption than ballastless slab track. They suggested that more emphasis be placed on the environmental effectiveness of railway transportation and that lifecycle analysis tools be applied to reduce environmental burdens.

The maintenance phase is an integral part of the lifecycle of railway systems. The level of use of machinery is an important factor in the generation of CO_2-e emissions in track bed maintenance. An investigation of the CO_2-e emissions from new high speed rail infrastructure construction in the USA was carried out by Chang and Kendall (2011). The authors found that the construction of bridges and tunnels contributed over 60 % of the total CO_2-e emissions from construction, with the tunnels and bridges occupying only 15 % of the total length of the project. The study concluded that the machines used in initial construction contributed 5 % of total CO_2-e emissions as compared to 80 % from the emission embodied in the materials. The authors concentrated on the construction of new rail infrastructures and excluded the maintenance phase.

Ueda et al. (2003) assessed the lifecycle of Shinkansen trains and sleepers in Japan. The authors found that timber sleepers emit the least CO_2-e compared with concrete, steel and synthetic sleepers. The authors did not investigate the impact of renewing the sleepers or the methodologies of renewals or maintenance.

Ballasted track has higher CO_2-e emissions from maintenance as the crushed aggregate requires increased maintenance compared to a ballastless track systems. Ballast cleaning and replacement involves replacing the crushed aggregates due to deterioration from cyclic loadings, fouling of the capping layer/ballast section or inadequate maintenance (Indraratna, 2009).

Von Rozycki et al. (2003) investigated the Hanover-Wuerzburg high speed rail line to determine the energy consumption of resources over the whole network including construction, vehicle manufacturing, maintenance, stations and train retrofitting. The authors found that the cumulative energy demand (defined as “the end material and end energy consumption to the primary energy drawn from nature at any stage of its lifecycle") of the infrastructure construction was responsible for 13 % of the total energy consumption. More importantly, it was found that the CO_2-e emissions associated with the material requirements for the Rheda ballastless track systems did not consume more energy than the ballasted track systems, as the extended life of ballastless track systems (60 year lifecycle) offsets the higher initial construction CO_2-e emissions, which results from the increased concrete requirement in ballastless track. This finding was confirmed by Kiani et al. (2008), who conducted an investigation into the lifecycle of both ballasted and ballastless track beds. The authors found that ballastless track was not associated with higher CO_2-e emissions. Because limited data was available at the time of publishing, the authors based their study on assumed maintenance intervals, fuel consumptions and construction speeds. Recognising that some of the assumptions considered a best case scenario and would not be practical for estimating much shorter renewal or maintenance projects, the authors made particular recommendations on further investigations into the fuel consumption of machinery used in construction and maintenance.

In summary, limited maintenance data has been published in the literature, with the use of assumptions to yield high level estimates. In order to verify the assumptions used in lifecycle emissions reporting, systematic first hand data collection and analysis are needed.

3 Methodology

3.1 Overview

The objective of the current study is to estimate the CO_2-e emissions during the plain-line railway maintenance phase and compared with that during the construction phase (Figure 1a). Focus is given to the collection and analysis of the CO_2-e emissions associated with the maintenance activities of ballasted track, due to the preference for ballasted track throughout Australia and the availability of appropriate sites. The data was collected from the field through interviews with construction managers, engineers and specialists and onsite observations, including assessment of cross sections, fuel consumptions, material lengths and lifespans, field based observations and construction methodologies. The results are compared to ballastless track systems from a previous study conducted by Kiani et al. (2008). A parametric study is then conducted to assess and forecast CO_2-e emissions from renewal projects by examining different track life scenarios and maintenance intervals.

The field based study did not include the analysis of CO_2-e emissions from the embodied emissions from the initial construction and earthworks, transportation and removal of materials, fuel from employees travelling to site, timber sleepers, disposal and the recycling of materials, calculation of the residual impact of the materials removed from the renewals and the manufacturing of the machines used in construction or maintenance. The scope of the current study is illustrated in Figure 1b.

Data collection was carried out on ballasted track renewal projects to evaluate the associated CO_2-e emissions associated with maintenance and renewal management practice and processes. The projects surveyed varied in difficulty and track length to ensure that a diverse range were captured for analysis.

3.2 Collection of Maintenance Project Management Data

All projects were carried out during weekend possession shutdowns. The maximum possession time is 50 hours; however, projects are usually completed well before the maximum time. Machines are delivered to site (applicable if machines are not road-worthy) and then remain on-site until the scheduled completion of tasks. All projects utilised small excavators and front end loaders until the completion of the works, all other machines were required for specific tasks only, such as digging substructure, levelling new sub-structure, removing rail, etc.

The travel requirements for machines involved in projects varies from site to site and this is difficult to estimate. Machines can travel from different maintenance yards, compounds and locations and therefore the travel distances and impact was excluded from the study.

3.3 Fuel Consumption Data Collection

Most machines used in rail maintenance and renewal are diesel engine driven. Hence diesel consumption is the main source of CO_2-e emission as far as the project activity is concerned. The fuel consumption is primarily proportional to the rate of consumption and the running time of the machines. The former is related to the type of machines and the latter to the project management and maintenance process.

The data collection was collected at five track renewal sites in the state of New South Wales in Australia.

- Project A consisted of a ballast cleaning project situated 35 km south of Sydney CBD. The project utilised a ballast cleaning machine and no major delays were recorded.
- Project B consisted of a ballast clean with new track laid with a track laying machine. The project was carried out 32 km south of Sydney CBD. Delays were experienced in obtaining track possession but this did not affect the final construction programme.
- Project C consisted of a manual dig and lay situated 22 km north of Sydney CBD. The excavation used a spoil train on the adjacent line with no delays recorded.
- Project D consisted of a manual dig and lay situated 25 km north of Sydney CBD. The excavation used a spoil train on the adjacent line with no delays recorded.
- Project E consisted of a manual dig and lay methodology and was situated 16 km west of Sydney CBD. The project had to cope with difficult access and site conditions. The project was next to a train station platform which made it difficult to remove and replace the ballast. The use of extra machines to remove and replace the materials was observed.

The data collection involved the identification of machines, their characteristic fuel consumption rates and their running times in various projects. Fuel consumption CO_2-e emissions were then calculated from the information collected.

3.4 Evaluation of GHG Emissions due to Fuel and Material Consumptions

A general equation for the evaluation of CO_2-e emissions relating to fossil fuel consumptions is given in DOE (2014) and is expressed as:

$$E_{ij} = Q_i C_i F_{ij} \tag{1}$$

where: E_{ij} is the amount of emission of gas species j relating to fuel type (kg).

Q_i is the quantity of fuel type i consumed by all the machines required on a project (kL).

C_i is the energy content factor of fuel type i (GJ/kL);

F_{ij} is the emission factor for gas j by fuel type i (kg/GJ).

In the current study, the primary focus is the carbon dioxide, methane, nitrous dioxide and the group of 4 synthetic gases (HFCs, SF_6, CF_4 and C_2F_6) emissions from diesel engines, hence i=diesel and j=1, 2, 3 corresponding to CO_2, CH_4, N_2O and the synthetic gas group. The corresponding parameter values are (DOE, 2014):

$C = 38.6$ GJ/kL;

$F_1 = F_{\mathrm{CO2}} = 69.2$ kg/GJ;

$F_2 = F_{\mathrm{CH4}} = 0.2$ kg/GJ;

$F_3 = F_{\mathrm{N2O+synthetic\ gases}} = 0.5$ kg/GJ;

The CO_2-e emissions of the maintenance work due to diesel fuel consumption is then evaluated from:

$$E = QC\sum_{j=1}^{3} F_j \tag{2}$$

Note that the index of subscript ‘diesel’ is dropped for simplicity without causing confusion.

For comparison analysis, the CO_2-e emissions are evaluated on the basis of unit track length of maintenance. Denote the length of track by T. The CO_2-e emission per unit track length of maintenance, E_u is defined by:

$$E_u = \frac{E}{T} \tag{3}$$

The CO_2-e emission associated with construction material consumptions per unit track length, or the embodied CO_2-e emission per unit track length EM (kg/m), is evaluated according to:

$$EM = \sum_{k=1}^{N} EF_k \ QM_k \tag{4}$$

where: k is material index

N is the total number of material types used in track construction

EF_k is the embodied emissions factor for type k material (kg/kg)

QM_k is the quantity of material k required per meter of track construction (kg/m)

3.5 Parametric Study

The purpose of the parametric study was to compare the maintenance CO_2-e emissions and the total lifespan CO_2-e emissions for three different track systems. It is noted that lifespan in the context of the current study only include the time period of construction and operation phases of the lifecycle. A given track system may have a different lifespan and different track length to others. A meaningful comparison would be to examine the CO_2-e emissions in terms of CO_2-e emissions per unit track length and per year of lifespan, which is defined as the CO_2-e emission lifespan measure and denoted as E_l (kg/m.year) and is evaluated according to:

$$E_l = \frac{E_m + E_{IC}}{L} \tag{5}$$

where E_m is the total CO_2-e emission due to maintenance per unit track length (including material embodied and maintenance fuel consumption) over the lifespan (kg/m) ;

E_{IC} is the CO_2-e emissions per unit of track length for the initial construction (kg/m); and

L is the given lifespan (year).

The maintenance CO_2-e emission per unit track length is a sum of the emissions due to materials and machinery, i.e., (EM_r + E_u), where EM_r denotes the embodied CO_2-e emission in materials used in the maintenance projects. Over a given life span a railway track will undergo a number of maintenance interventions which may consist of different activities. Introduce a maintenance type index n. For a known M types of maintenance activities, the maintenance CO_2-e emission per unit track length over a lifespan is evaluated from:

$$E_m = \sum_{n=1}^{M} \left(\frac{L}{MF}\left(EM_r + E_u\right)\right)_n \qquad (6)$$

Where n is the maintenance activity index;

MF is the maintenance frequency.

The CO_2-e emissions per unit of track length for the initial construction is evaluated from

$$E_{IC} = EM_{ic} + E_{CM} \qquad (7)$$

where E_{CM} is the CO_2-e emission per unit track length for construction machinery.

EM_{ic} is the CO_2-e emission per unit track length for materials used in initial constructions (kg/m).

4 Results and Discussions

4.1 Maintenance management data

The machines included in the data collection are listed in Table 1. Both projects A and B used a ballast under-cutter and track laying machine and Projects C, D and E used a manual dig and lay method which involved excavators and drotts (or bulldozer) removing and replacing the ballast and a bobcat and excavator replacing the sleepers. Front end loaders were used to place the steel rail into position.

Interviews with railway engineers and project managers were carried out to determine the characteristics of materials used in railway systems. It was found that materials can last well above the design life (examples of steel rail being used in practice for over 75 years), with this data considered in the maintenance frequencies in Section 3.5. The fuel consumption values were obtained from the machine operators after the completion of the projects. These values were substituted into Eq. (1) to obtain estimates of the CO_2-e emissions and the results are presented in

Table 3. The material requirements per metre for ballasted and two ballastless track types are shown in Table 2.

4.2 Machinery and CO_2-e Emission from Ballasted Track Renewal

The machines and quantities used in projects A to E are shown in Table 1. The results show that project E required the use of extra machines due to the difficult site conditions. The greatest unpredictability in the construction programme is the time taken to remove and replace the substructure. Specialised machines such as ballast under-cutters and track laying machines can reduce the times, as can pre-fabricated materials components. The length of track to be renewed is an important consideration in maintenance project management as the time available to complete the works is limited.

The total CO_2-e emissions and emissions per unit length of track maintenance from the five projects are listed in Table 3. Project E had the highest levels of total CO_2-e emissions and emission per track length, due to the difficult site conditions and the need for extra machinery on site (see Table 1).

Project E produced 53.63 kg CO_2-e emissions per metre of track. The machines used in project A and B contributed 78 % and 86 % less CO_2-e emissions per metre of track when compared to project E. The reduction in emissions are due to the use of the ballast under-cutter and track laying machines which increased the efficiency in both projects A and B. Project C and D contributed 53 % and 33 % less CO_2-e emissions respectively per metre of track when compared to project E as the processed track lengths were relatively short in the former two projects and a manual dig-and-lay construction methodology was used in lieu of ballast under cutters and track laying machines.

The average CO_2-e emissions rates from projects A to E is shown in Table 3. The average CO_2-e emissions per unit length of track were used in the parametric study to ensure the data included an allowance for different construction methodologies and machinery.

4.3 Material Impacts on Ballasted Track Plain-line Construction Projects

In this analysis, plain-line renewal projects involved replacing and upgrading sections of ballasted track bed. The materials requirements for each metre of track and the embodied emissions factors are listed in Table 4. The embodied CO_2-e emissions from materials were estimated using the embodied emissions factors obtained from the ICE (2011) database and Eq. (4). The material quantities have been estimated based on the cross sections shown in Figure 2a for ballasted track. Projects A to E used the same track bed cross section and therefore the embodied energy per metre of track is the same.

5 Discussion

Table 5 shows the total CO_2-e emissions and the fraction contributions from fuel and materials for Projects A to E. It is seen that materials contributed more CO_2-e emissions than fuel consumption from machines in the renewal projects. The embodied emissions in steel and concrete production are the source of greater CO_2-e emissions from the material components. The results show that Project B (total length of 1375 m) has the lowest percentage of fuel CO_2-e emissions when compared to the material emissions. The distribution share of emissions was 2 % and 98 % respectively, due to the lowest fuel consumption per metre (see Table 3). The emissions from Project E (281 m in length and highest fuel consumption rate per metre, Table 3) shows that machines have a 10 % contribution of CO_2-e emissions and materials contribute 90 % of the total CO_2-e emissions.

No maintenance project is a carbon copy of another. Many factors, including the project scale, the maintenance method and the detailed process, varied from project to project. These variations were reflected in the fuel consumption with the random attribute as is seen in both E_u presented in Table 3 and in the fraction contribution to the total CO_2-e emission presented in Table 5. Notwithstanding, the range of variation from 2 % to 10 % fuel contribution fraction of CO_2-e emission in the maintenance of the ballasted track is comparable with the result (18 %) obtained by Chang and Kendall (2011) for the initial construction phase. The lower value of the current study may be attributable to the exclusion of other factors such as travel and material transportation.

Kiani et al. (2008) found that the CO_2-e emissions from ballastless track over the lifecycle were not associated with increased CO_2-e emissions when compared to ballasted track bed. Kiani et al. (2008) concluded that ballasted track construction CO_2-e emissions were a little more than half of the ballastless track construction CO_2-e emissions, however, maintenance activities including ballast cleaning, ballast resurfacing and renewals increased the lifecycle CO_2-e emissions to similar levels.

The data collected was a small sample due to the limitations of weekend shutdown work, the difficulty in accessing sites with large volumes of machinery movements and the costs associated with the data collection. A degree of uncertainty is associated with any construction project and to solely implement the results of this study in a life-cycle emissions assessment would be crude and imprecise. Nonetheless, the sample data could be used to conduct statistical analysis to provide descriptions of the characteristics.

Monte Carlo simulation would be an appropriate method to carry out the analysis (Coelli, 1995). The difficulty, however, in relying on values from a small sample size is the discrepancies in the fuel consumption from the data collection. It may be plausible to assume that the data collection projects in this study covered a reasonable range of case scenarios from the relative simple projects A and B to the more intricate project E. A statistical analysis would then be applied to ensure a degree of certainty is established in the data results and the data could be used with confidence in the future studies.

6 Parametric Study

Routine maintenance activities such as ballast tamping and rail head grinding have the capacity to increase component life, with Milford and Allwood (2011) concluding that by extending the life of railway tracks through maintenance, CO_2-e emissions per year of their lifespan may be reduced. A parametric study was carried out to analyse the impact of the maintenance and renewal of railway track on CO_2-e emissions over time. The study compared the construction and maintenance portion of the lifecycle emissions from ballasted track, Rheda 2000 cast-in sleeper concrete slab track and Balfour Beatty embedded slab track (BBEST).

Table 6 shows the frequencies of maintenance activities used in the parametric study. The frequencies are used to ascertain the maintenance commitments for the lifecycle of the infrastructure. For ballasted track, the major track renewal interval is assumed to be 40 years and two renewals are conducted. As a result, the ballasted track lifespan is 120 years. The replacement of rails in the ballasted track was assumed to be with the renewal projects (at a 40-year interval), as in practice. Ballast cleaning and replacement was set at 20 years after construction and re-construction. Ballast resurfacing is considered on a 4 year interval.

For the ballastless tracks the lifespan is set at 100 years. The main maintenance activities on ballastless track are rail grinding and rail replacement. Milford and Allwood (2010) explained that 60 kg/m steel rail had the potential to last 13 - 38 years, depending on axle loads, wagon suspension and train frequencies. The parametric study considered a 25 year interval for replacing steel rail in the ballastless track types. A conservative rail replacement interval has been used due to the higher speeds in ballastless track types and the more frequent requirement of rail head grinding.

The maintenance frequencies are used to calculate the total emissions with the E_m rate in Table 6. The CO_2-e emissions per unit length of track maintenance obtained from the data collection as shown in Table 3 are used to determine the total emissions over the lifespan of the ballasted track.

Figure 3 illustrates the CO_2-e emissions from maintenance per unit of track of the ballasted track, Rheda 2000 track and BBEST over a lifespan. The ballasted track has a lifespan of 120 years, whilst the ballastless tracks are assumed to be 100 years. Results were generated at the time of 30 years, 60 years and end of the lifespan. It can be seen at 30 years, the construction and maintenance of ballasted track was 54 % and 55 % less emissions than the Rheda 2000 and BBEST systems respectively. This is due to the greater emissions from the construction of the ballastless track types.

At the 60 year interval, the ballasted track system emits 29 % and 31 % less CO_2-e emissions compared to Rheda 2000 and BBEST respectively. In this time period, the ballasted track bed required a full track renewal and two ballast cleaning interventions in the time period compared to only a rail renewal in the Rheda 2000 and BBEST track.

At the end of lifespan the ballasted track emitted 13 % and 15 % less CO_2-e emissions than the Rheda 2000 and BBEST systems respectively as indicated in Figure 3. The Rheda 2000 emitted 2 % less CO_2-e emissions than the BBEST system. The greater CO_2-e emissions from the BBEST over the Rheda 2000 system is attributed to the larger material cross section of the two ballastless construction types.

As the lifespan prolongs the maintenance emission (E_m) of ballasted track increases faster than that of the other two systems. Hence, the total emissions (E_m+E_{IC}) of the ballasted track increased faster after the initial construction to the end of life, as expected due to the increased maintenance requirement. Overall, the comparison of the three track types show that the ballasted track maintenance CO_2-e emissions were the least when compared to Rheda 2000 and BBEST over the whole lifespan. The ballast material requires more frequent and complicated maintenance to ensure effective and safe train operations. On the other hand, the ballastless track types emit greater emissions during construction and this is shown in the increased overall emissions. It is also noted that the disposal of the materials are excluded from the study due to the limitations and complexity of including these in the study.

Although Figure 3 reveals the differences in CO_2-e emissions between the three track types, it actually gives a biased comparison since the three tracks were evaluated at different lifespans. A meaningful comparison should be made on the basis of CO_2-e emission lifespan measure, E_l (or CO_2-e emission per unit track length per year of lifespan), as presented in Figure 4. It is revealed that over the 30 years, 60 years and end of lifespan, the ballasted track emits the least greenhouse gas per unit length of track and per year of lifespan. Table 7 shows the percentage ratio of various emission lifespan measures of various tracks to that of ballasted at the 30, 60 and end of life intervals. It is seen that for the 30 and 60 year time intervals Rheda 2000 and BBEST emit 14 % and 17 % more CO_2-e emission respectively than ballasted track. At the end of life, these differences are increased to 37 % and 41 % respectively.

7 Conclusion

This study evaluated the CO_2-e emissions from ballasted track bed maintenance and renewal activities. The evaluation was based on a field survey which covered a range of site scenarios. The results were analysed and compared with that of two ballastless track bed systems.

The data collected from the ballasted track site surveys showed that the machinery CO_2-e emissions varied from 2 % to 10 % of the total CO_2-e emissions of the projects. The material component of renewal project contributes the most CO_2-e emissions due to embodied emissions in material production. This is a similar result to that of the study carried out by Chang and Kendall (2011) for the initial construction phase of the lifecycle.

In ballasted track, steel rail and concrete sleepers contributed 92 % of the total materials CO_2-e emissions, therefore the lifecycle CO_2-e emissions of steel rail and concrete sleepers could be reduced if an increase in service life was achieved.

Albeit the initial objective was to reduce the uncertainties associated with the assumptions in previously used estimates, the results of the current study have revealed that the greenhouse gas emission per unit track length of maintenance due to fuel consumption is a random variable. It varies from project to project for the same track system. Any attempt to use an assumed average for the analysis of a general project would be a crude approach and the result would contain a degree of uncertainty.

Despite the total emission of the three track systems increase with lifespan, their lifespan measures diminish with the prolonging of lifespan. However, the differences in the three track systems increase with lifespan in terms of CO_2-e emission per unit track length per year of lifespan increases. The ballasted track appears to be the best performer to have the lowest lifespan measure. In comparison, the BBEST has the highest emission per lifespan measure.

A number of emission contributing factors, such as fuel consumption in travel to maintenance sites and the demolition, disposal or recycling of materials from the renewal projects, were not included in the current study. These factors can be included in future studies. Recommendations for future work also include a survey study on the construction of ballastless track systems to obtain more reliable results for comparison with ballasted track bed construction. It would be desirable to collect and analyse data from more maintenance projects to obtain more reasonable estimates of the random behaviour of the key indicators such as CO_2-e emission per unit track length of maintenance of any type. Furthermore, statistical or Monte Carlo simulation studies can be conducted to understand the uncertainty associated with the parametric study.

The input parameters of the parametric study were based on the existing and newly obtained information. It can be certain that the technological advancement in the future will result in changes in materials, tools and practice for the construction and maintenance of railway systems. Further development of the model would be necessary to take technological advancement into account for estimating greenhouse emissions.

Acknowledgements

The authors would like to thank the University of Western Sydney for funding of this work. Special thanks to all assistance from Railcorp, Anric Rail, Dave Ormsby Haulage Pty Ltd, C and L Sultana Earthmoving and G & S cranes for assistance in fuel consumptions, Mr. Wai Chung Mok from UWS and all work group leaders and engineers for their assistance in worksite data collection. Valuable comments from Professors Joseph Sussman and Hurbert Einstein (MIT CEE) are gratefully acknowledged. The last author wishes to thank Australian Government for his Endeavour

Executive Fellowships at Massachusetts Institute of Technology, at Harvard University, and at Chalmers University of Technology.

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Table 1. Machines and their numbers used in the five surveyed projects.

Machine used	Project A	Project B	Project C	Project D	Project E
Ballast under-cutter	1	1			
Bobcat	1	2	1	1	1
Excavator (6 tonne)	2	2	1	1	2
Excavator (14-16 tonne)	1	4	3	3	4
Drott		1	1	1	3
Dump truck (5 tonne)	2	2	1		2
Dump truck (14 tonne)		2			7
Front end loader	2	2	3	2	3
Grader	1	1			
Regulator	1	1	1	1	1
Smooth drum roller	1	1	1	1	1
Stabiliser	1	1	1	1	
Tamper	1	1	1	1	1
Tipper bogie		1			8
Track jack	1	1	1		
Track laying machine	1	1			
Total number of machines used	16	24	15	12	33

Table 2. Material requirements for various track beds.

Type of Track System	Material	Weight per Metre of railway track (kg/m)	Source
Ballasted – Heavy duty sleepers (Figure 2a).	Road base	1272	Current study
	Ballast	2067	Current study
	Concrete sleepers	561	Current study
	Steel rails	120	RailCorp (2012)
	Resilient plastic pads	1.74	Current study
	Insulators	0.24	Current study
	Steel e-clips	5.44	Current study
Rheda 2000 slab track system: Cast in sleeper with concrete foundation and exposed rail (Figure 2b).	Reinforcing bars	21.54	Kiani et al. (2008)
	Aggregate	3346	Kiani et al. (2008)
	Cement	348	Kiani et al. (2008)
	Steel rail	120	Kiani et al. (2008)
	Rail pads	1.02	Kiani et al. (2008)
	Fastenings	30.8	Kiani et al. (2008)
BBEST System: Concrete sub-base and foundation with embedded rail (Figure 2c).	Mass of reinforcing steel	116	Kiani et al. (2008)
	Aggregate	2140	Kiani et al. (2008)
	Cement	366	Kiani et al. (2008)
	Shell	5	Kiani et al. (2008)
	Seal	0.4	Kiani et al. (2008)
	Grout	55	Kiani et al. (2008)
	Resilient pads	1.7	Kiani et al. (2008)
	Steel Rails	148	Kiani et al. (2008)

Table 3. Recorded project data and results of CO$_2$-e emission from machinery usage.

Project	T (m)	Q (L)	E (kg)	E_u (kg/m)
A	551	2460	6637	12.05
B	1375	3701	9986	7.26
C	170	1594	4301	25.30
D	135	1846	4981	36.90
E	281	5585	15069	53.63
Average	503	3038	8195	27.03

Table 4. Embodied emissions factors (ICE Database, 2011) and the evaluated embodied carbon emission per unit length of track.

Materials	***EF*** **(kg/kg)**	***QM*** **(kg/m)**	***EM*** **(kg/m)**
Roadbase	0.0051	1272	6.49
Ballast	0.005	2067	10.34
Concrete Sleepers	0.277	561	155.40
Steel Rail	2.78	120	333.60
Plastic Pads	3.0	1.02	3.06
Insulators	3.0	0.68	2.04
Resilient e-clips	2.78	5.44	15.13
Total			526.06

Table 5. Total and fraction of CO$_2$-e emissions from materials and machinery.

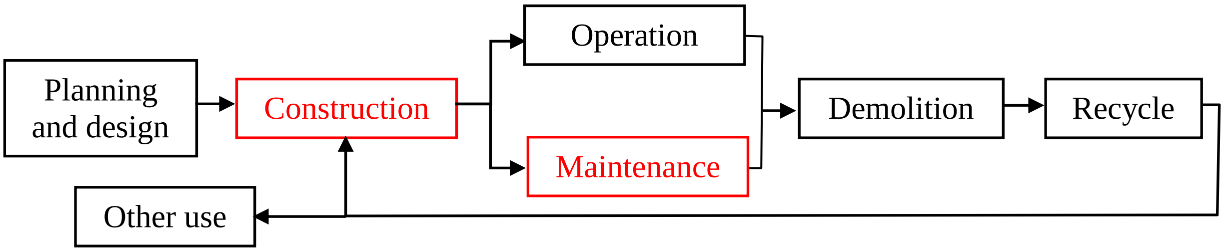
Project	Total CO$_2$-e emissions (kg)	Fraction of machinery contribution	Fraction of material contribution
A	290,171	3 %	97 %
B	724,111	2 %	98 %
C	89,527	6 %	94 %
D	71,095	6 %	94 %
E	147,982	10 %	90 %

Table 6. Maintenance intervals (Milford and Allwood, 2011 and Kiani et. al., 2008) used in parametric study and CO$_2$-e emissions from maintenance as per data collection.

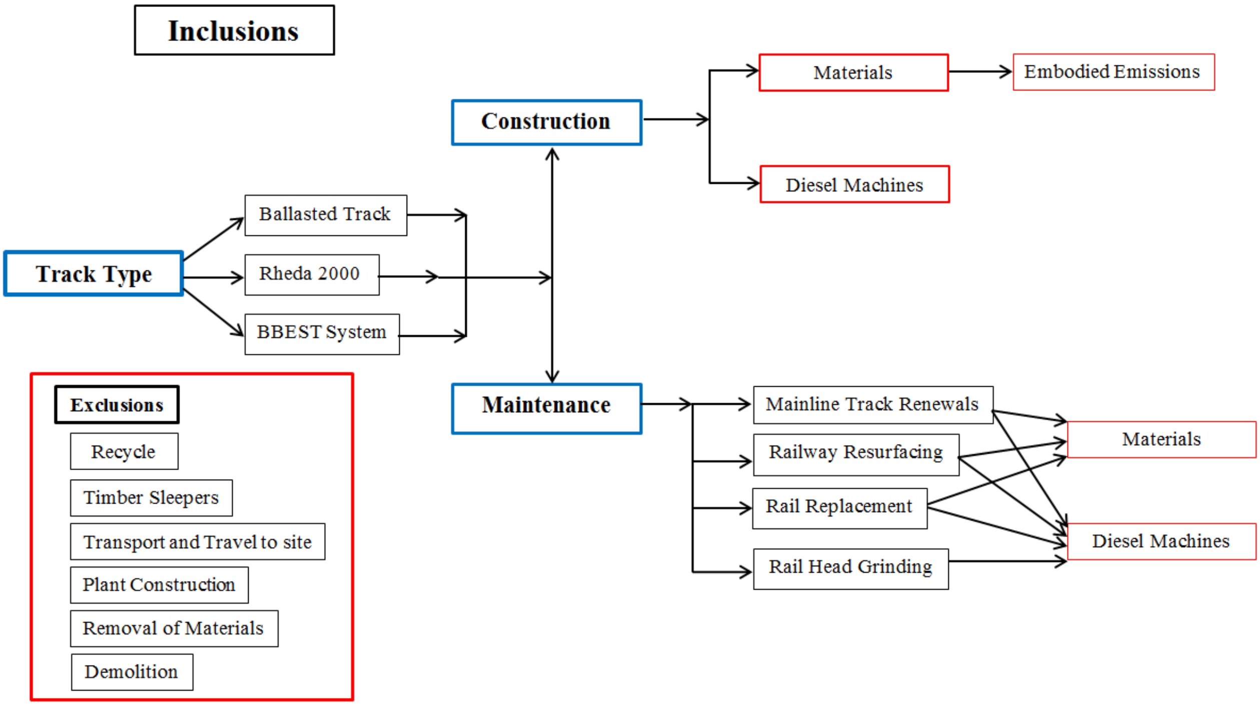
Maintenance activity	**Track type and maintenance intervals (year)**			**E_m rate for track maintenance (kg/m)**
	Ballast Track	**Rheda 2000**	**BBEST**	
Track renewals	40	N/A	N/A	554
Rail head grinding	2	1	1	0.53
Rail Replacement	with renewal	25	25	336
Ballast resurfacing	4	N/A	N/A	1.17
Ballast cleaning / replacement	20 - alternating with renewal	N/A	N/A	11.83

Table 7. Comparison of CO_2-e emission lifespan measure relative to that of ballasted track at different period.

Track type	30 year (%)	60 year (%)	End of lifespan (%)
Ballasted track	100	100	100
Rheda 2000	114	114	137
BBEST	117	117	141

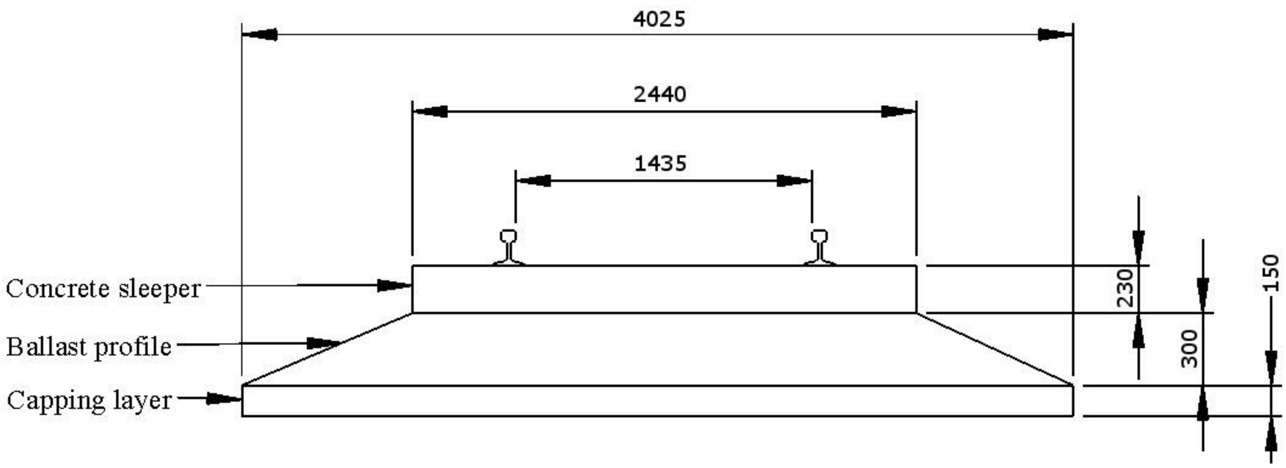


a. Typical lifecycle of a railway system and the phases included in the current study (in red).

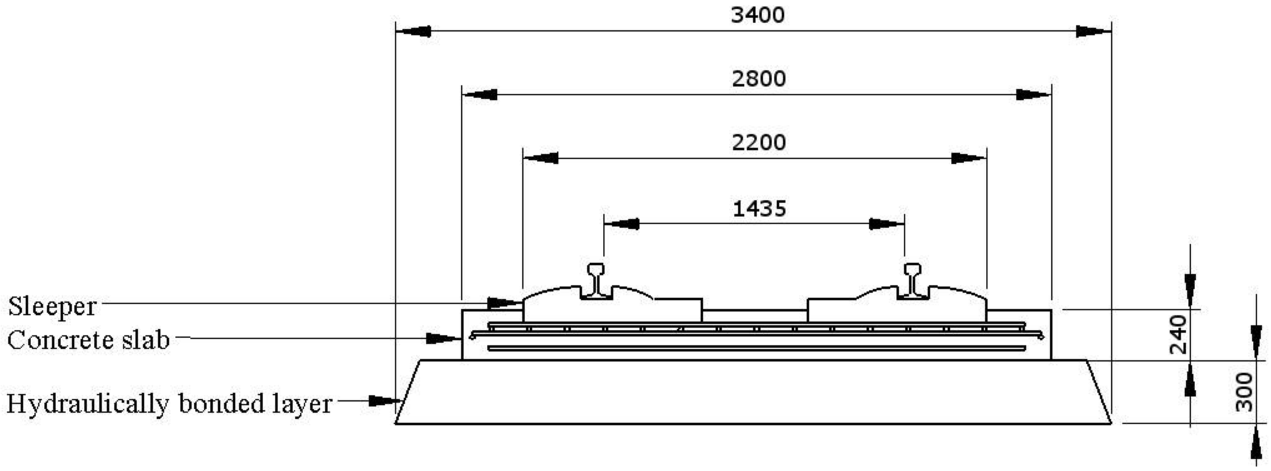


b. Scope of the maintenance CO_2-emission estimate in the current study.

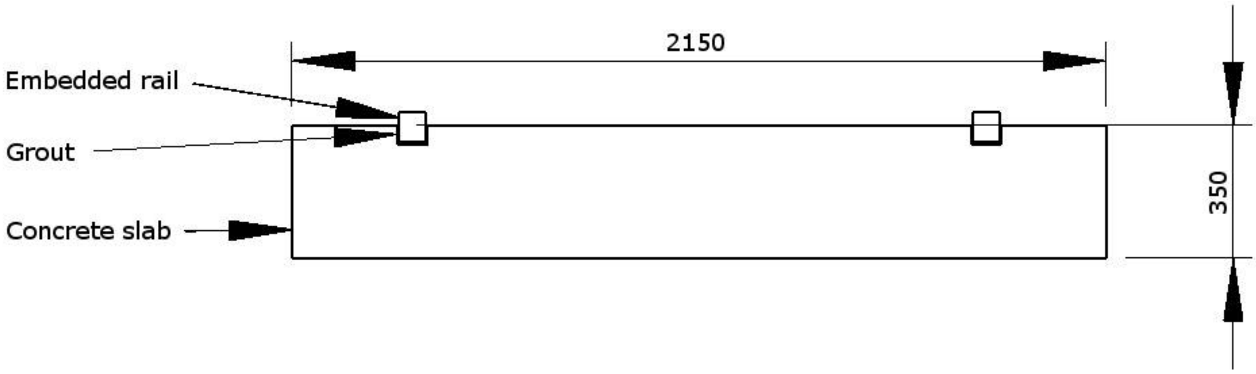
Figure 1. Lifecycle of railway systems.



a. Ballasted track bed construction cross section (Courtesy Railcorp, 2012)



b. Rheda slab track system construction cross section (courtesy Rheda, 2000).



c. Embedded slab track construction cross section.

Figure 2. Illustrations of three types of railway track bed constructions.

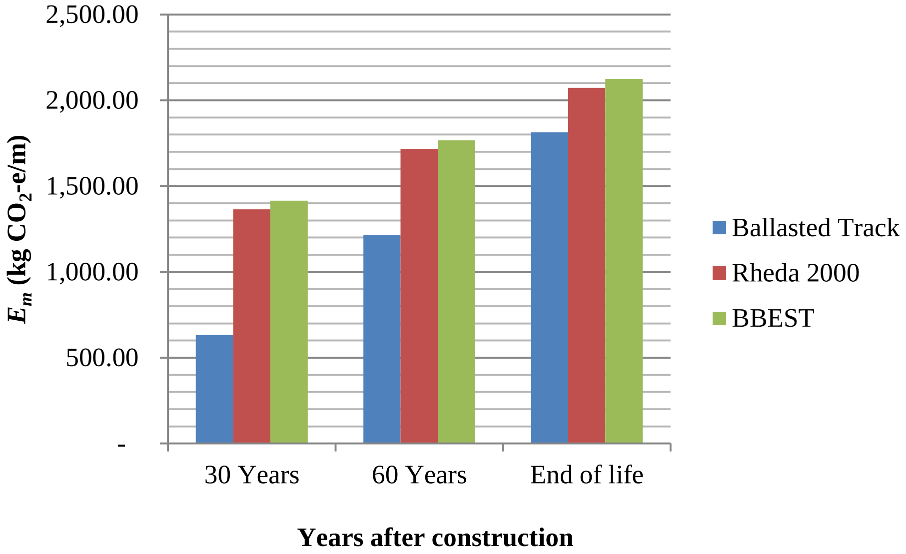


Figure 3. Total CO_2-e emissions from maintenance activities per unit length of three track systems over different lifespans.

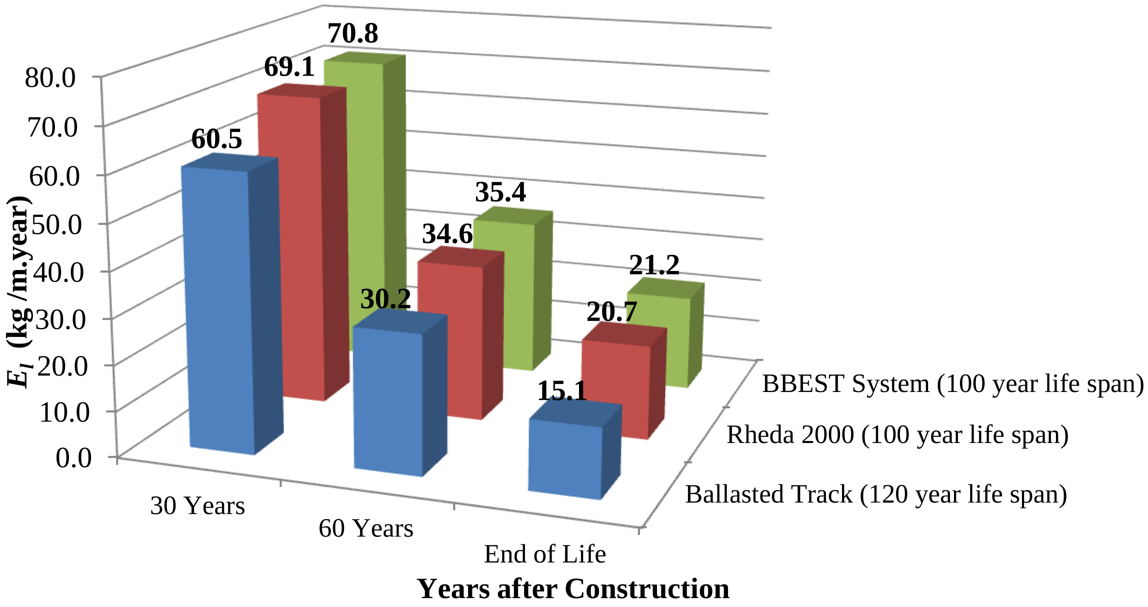


Figure 4. Results of E_l for the three track types.