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A Whole Life Carbon Model for Railway Track System Interventions

by

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Abstract

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The aim of this thesis is to develop an integrated methodology for investigating the potential for a range of novel interventions to reduce the whole-life carbon footprint and Life Cycle Costs (LCC) of ballasted track. Existing methods for assessing the socio-economic performance of railway infrastructure have often been found wanting.

A review of the academic literature in the field has been undertaken and methodologies with the potential to improve the socio-economic modelling of railway infrastructure have been identified. A modelling framework for environmental and financial appraisal has been developed by combining principles of Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) approaches. Its applicability has been tested through a range of exemplar case studies.

The framework has been first tested at the component level, by examining the whole life carbon footprint and LCC of the four most common railway sleeper types present in the UK railway network. Then it has been expanded, by incorporating a detailed Life Cycle Inventory (LCI) inventory of different Switch and Crossing (S&C) design variants. This enabled the quantification (at the asset level) of the whole life carbon footprint and carbon costs of fifteen (six turnouts and nine crossovers) designs variants.

The framework was then extended with the capability of examining the performance of novel modifications to the conventional ballasted track. A methodology based on relative settlement was proposed to adapt the results of laboratory element tests into a suitable input into an existing industry-based track geometry degradation model, allowing the estimation of the carbon footprint and Life Cycle Costs (LCC) at the route level. Finally, test results were applied to two practical case studies, demonstrating the capabilities of the model in evaluating and comparing the long-term performance from the inclusion of seven novel track interventions, so as to assess the case for altering current practice.

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Declaration of Authorship

I declare that this thesis and the work presented in it is my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
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Acronyms

ADEME Agence de la transition écologique (Agency for Ecological Transition). 12

AF Annuity Factor. 49

AIRR Adjusted Internal Rate of Return. 49

ANN Artificial Neural Network. 48, 191

BAU Business as Usual. 103, 104, 123, 125

BCF Ballast Condition Factor. 32, 145

BCR Benefit Cost Ratio. 49

BIM Building Information Modelling. 24

BOF Basic Oxygen Furnace. 108

BoM Bill of Materials. 100, 187

BoQ Bill of Quantities. 100, 187

BSB Bitumen Stabilised Ballast bound with bitumen emulsion. 19

CapEx Capital Expenditure. x, 3, 88–90, 92, 135

CBA Cost Benefit Analysis. 7, 35, 36, 53, 183

CC Carbon Costs. 173, 176, 179

CE Circular Economy. 191

CF Carbon Factor. 21, 62, 64–66, 72, 76, 99, 101, 105, 149

CFs Carbon Factors. xiii, 21, 66, 71, 81–83, 98, 99, 103, 146, 149, 151

CMS Carbon Management System. 27

CPI Consumer Price Index. 88

CR Conventional Railway. 10, 11, 13

CRM Crumb Rubber Modified mixture. 19

DBEIS Department for Business, Energy and Industrial Strategy. 67, 103, 151

DEFRA Department for Environment, Food and Rural Affairs. 17, 66

DfT Department for Transport. 25

DPB Discounted Payback. 49, 173, 176, 177, 179

DSS Decision Support System. 29, 31

EAF Electric Arc Furnace. 108

EC Embodied Carbon Dioxide. 64, 67, 68, 75, 76, 78, 80, 99, 108, 109, 149

ECML East Coast Main Line. xi, xiv, 56, 146, 155, 156, 158–161, 163, 165, 166, 169–171, 173, 175–177, 179, 181, 188

EF Emission Factor. 67, 70, 82, 83, 101, 103, 104, 146, 151, 152

EFs Emission Factors. xiii, 12, 17, 18, 23, 26, 27, 62, 66, 68, 95, 103, 104, 149

EIO-LCA Economic Input-Output Life Cycle Assessment. 4, 44

ELR Engineering Line Reference. 56

EMGTPA Equivalent Million Gross Tonnes per Annum. 22, 65, 74, 76–80, 83, 87, 89, 90, 95, 155

EoL End-of-life. 13, 16, 19, 33, 43, 44, 62, 63, 69, 70, 74, 76, 79, 80, 84, 92, 94, 99, 107, 108, 116, 118, 121, 125, 126, 134, 135, 146, 147, 151, 186, 187, 191

EPSRC Engineering and Physical Sciences Research Council. xvii

ETA Event Tree Analysis. 48

EVA Ethylene-Vinyl Acetate. 91

FCA Full Cost Accounting. 52

FCEA Full Cost Environmental Accounting. 52

FCP Full Cost Pricing. 52

FFU Fiber-reinforced Foamed Urethane. 24

FMEA Failure Mode and Effects Analysis. 48

FMECA Failure Mode, Effects and Criticality Analysis. 48

FTA Fault Tree Analysis. 48

FU Functional Unit(s). 9, 33, 38, 40, 42, 44, 61, 63, 69, 72, 80, 101, 103–105, 147, 149, 151, 152

FY Financial Year. 1, 95

GeoGIS Geography and Infrastructure System. 17

GHG Greenhouse Gases. 10, 13, 20, 21, 25, 27, 62, 71, 80, 85, 92, 94, 115, 116, 120, 121, 123, 126, 128, 129, 134, 160, 165, 180, 185–188, 190

GIS Geographical Information System. 10, 191

GWML Great Western Main Line. 56

GWP Global Warming Potential. 24, 70, 79

HAZOP Hazard and Operability study. 48

HGV Heavy Goods Vehicle. 103

HSL High Speed Line. 11–13

HSR High Speed Rail. 4, 11–14

IBCL In Bearer Clamp Lock. 100

IM Infrastructure Manager. 30, 57, 88, 91, 170, 191

IMs Infrastructure Managers. 5, 185

IRR Internal Rate of Return. 7, 49, 168, 173, 176, 177, 180, 188

LCA Life Cycle Accounting. 52

LCA Life Cycle Assessment. iii, ix–xi, xiii, 3–5, 7, 9, 11–15, 17–20, 24–27, 33, 35–44, 51, 52, 57, 58, 61–63, 69, 72, 76, 78, 79, 81, 93, 95, 98, 115, 118, 135, 146, 147, 151, 183, 184, 187

LCC Life Cycle Costing. 36, 45, 51, 52, 57

LCC Life Cycle Costs. iii, x, xi, 1, 6, 7, 13, 19, 24, 27–31, 45, 50–52, 54, 57, 58, 88–90, 92, 135, 137, 167, 168, 170–175, 180, 181, 183–186, 188–190

LCCA Life Cycle Cost Assessment. iii, 3, 7, 9, 27, 33, 35, 45, 46, 48, 51, 52, 57, 58, 61, 93, 135, 183, 184

LCI Life Cycle Inventory. iii, xiii, xiv, 13, 27, 39, 41, 58, 93, 100, 108, 134, 148, 150, 154, 157, 183, 187, 190

LCIA Life Cycle Impact Assessment. 41

LTSF Local Track Section Factor. xiv, 32, 139, 145, 146, 156, 169, 170

MART Mean Active Repair Time. 47

MCA Multi-Criteria Analysis. 33

MCS Monte Carlo Simulation. xiv, 28, 30, 48, 58, 85, 86, 130, 131, 176, 177, 179, 181, 184, 185, 190

MDT Mean Down Time. 47

MFCA Material Flow Cost Accounting. 53

MILP Mixed Integer Linear Programming. 27, 28

MLDT Mean Logistic Delay Time. 47

MMH Mean Maintenance Hours. 47

MML Midland Main Line. 56

MTBCF Mean Time Between Critical Failure. 47

MTBF Mean Time Between Failure. 47

MTBM Mean Time Between Maintenance. 47

MTBR Repair Time or Mean Time Between Repair. 47

MTBSAF Mean Time Between Service Affecting Failure. 47

MTFF or MTTFF Mean Time To First Failure. 47

MTTF Mean Time To Failure. 47

MTTM Mean Time To Maintain. 47

MTTR Mean Time To Repair. 47

NPE Net Present Emission. 37

NPV Net Present Value. xi, 7, 31, 37, 49, 52, 53, 168, 170–173, 176–178, 180, 188

NR Network Rail. 3, 7, 17, 18, 31, 32, 55, 56, 64, 68, 95, 97, 100, 105, 139, 142, 169, 181, 185, 187

NS Net Savings. 12, 49

NTV Net Terminal Value. 49

OAT One-at-a-Time technique. 84

OpEx Operational Expenditure. x, 88–90, 92, 135

ORR Office of Rail and Road. 3

P/C Plastic Composite. 20

PAHs Polycyclic Aromatic Hydrocarbons. 80

PHA Preliminary Hazard Analysis. 48

PKT passenger-km travelled. 4, 12, 14, 15

PMT passenger-mile travelled. 14

PN Petri Nets. 28–30, 191

PPM Passenger Performance Measure. 47

RAMS Reliability, Availability, Maintenance and Safety. xiii, 7, 28, 46–48

RAP Reclaimed Asphalt Pavements. 19

RCF Rolling Contact Fatigue. 32, 56, 97

RFRs Random Fibre Reinforcements. 142, 143, 145, 148, 155, 165, 169, 170, 174, 177, 180, 188

ROCE Return On Capital Employed. 49

RPS Re-Profiled Shoulder. 142, 165, 169, 170, 173, 174, 177, 180, 188

RRVs Road Rail Vehicles. 102, 115

RSSB Rail Safety and Standards Board. 64, 66, 99, 103, 149, 151

S&C Switch and Crossing. iii, xiii, 6, 7, 54, 58, 93–95, 115, 116, 118, 121, 130, 134, 160, 167, 169, 173, 176, 177, 187, 189, 190

S&Cs Switches and Crossings. ix, 6, 7, 24, 33, 34, 54, 55, 93–95, 104, 106, 109, 126, 134, 154, 189

SB System Boundary. xi, xiii, 15, 16, 38–40, 44, 61, 62, 69, 80, 93, 98, 146, 147

SD Standard Deviation. 29, 31, 138, 139

SIR Savings to Investment Ratio. 49

SNCF Société Nationale des Chemins de fer Français (French National Railway Company). 12

SPB Simple Payback. 49

SRTF Southampton Railway Testing Facility. 140–142

stkm Single Railway Track Kilometre. 62, 64, 85, 86, 88, 91, 92, 186

SWML South West Main Line. 56

T-SPA Track - Strategic Planning Application. 31, 32

T2F Track to the Future. 31

TACC Total Annual Capital Charge. 49

TCA Total Cost Accounting. 52

TCA Total Cost Assessment. 52

TID Track Identification. 56

TMT track-mile travelled. 14

TPE Transpennine Express Route. 56

USP Under Sleeper Pad. x, xiii, 24, 74, 90–92, 100, 105, 139, 141–143, 148, 155, 165, 169, 170, 176

USPs Under Sleeper Pads. 165, 169, 170, 174, 177, 180, 186, 188

VBA Visual Basic for Applications. 74, 94

VKT vehicle-km travelled. 4, 14

VTIs Vehicle Track Interaction models. 139

VTISM Vehicle Track Interaction Strategic Model. xi, 7, 17, 18, 31, 32, 56, 64, 155, 156, 169, 180, 185, 191

W-SPA Wheelset Strategic Planning Application. 31

WLC Whole Life Costing. 52

WLCC Whole Life Cycle Costing. 28, 45, 88, 92

WLRM Whole Life Rail Model. 31, 56

WPDM Wheel Profile Damage Model. 31

Chapter 1

Introduction

1.1 Infrastructure Challenges : with both eyes open

In the UK, almost 1.76 billion rail passenger journeys were made in the Financial Year (FY) 2018 – 2019, with rapid growth from 1.59 billion passenger journeys five years earlier (ORR, 2019a). Nonetheless, the Coronavirus (COVID – 19) outbreak that shut down the world in late 2019, resulted in sizeable losses for the rail industry, plummeting annual rail passenger journeys in the UK to 0.39 billion (2020 – 2021) (ORR, 2022b). These figures started rebounding ever since, but remain well below their pre-pandemic levels. However, there are concerns that rail could lose its principal advantages over other transport modes with respect to journey time reliability and environmental sustainability if it does not continually improve. For example, in the UK maintenance costs are higher than elsewhere in Europe (McNulty, 2011). Along with increasing fiscal constraints, this means that there is growing pressure on the UK rail industry to find ways to reduce its costs. There is also uncertainty over whether the railway system will be able to cope with predicted future demand (Ison et al., 2012) on a network whose overall size in terms of mainline route length has remained essentially static for several decades (ORR, 2019b). To address these and other concerns Powrie (2014) suggested targeting opportunistic and achievable improvements on the railway system that allow faster and heavier trains with less maintenance requirements.

The type of railway track system used on a given route will affect its maintenance costs. Broadly speaking there are two established types of railway track around the world: ballasted track and slab track (Esveld, 2001; Indraratna et al., 2011). In the first case, the rails distribute the load to the sleepers and the sleepers do the same to a bed of stones, called ballast (Burrow et al., 2007), while in the second case the rails are supported by concrete slabs. In all cases maintenance activities are needed to extend the life of the rail infrastructure by maintaining an acceptable geometry for the safe operation of trains and tolerable passenger comfort. In the UK, the vast majority of railway routes use ballasted track (Figure 1.1). Whilst this type of track system offers great advantages, such as lower initial investment cost and the possibility to adjust and replace sections of track more easily than slab track (Indraratna et al., 2011), it also has more frequent maintenance needs, which could lead to higher Life Cycle Costs (LCC) and may be less energy efficient over long timescales (Kiani et al., 2008). There has therefore been an ongoing body of research in recent years aimed at reducing maintenance requirements for ballasted track. However, while a number of potential interventions have been proposed and sometimes tested, it is often not clear whether the savings they generate outweigh the initial costs of installation.

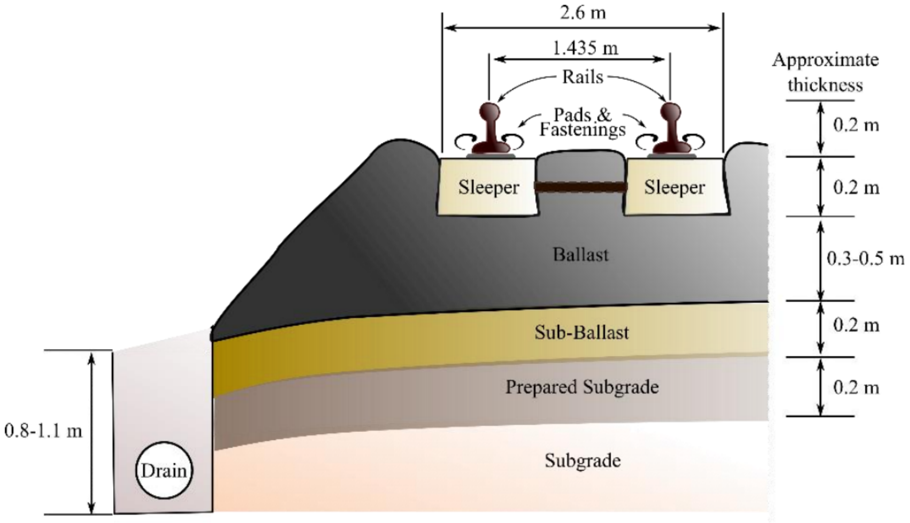

FIGURE 1.1: Ballasted track.
Sources: Milne (2017)

1.2 Sustainable Infrastructure : without the hot air

Growing carbon emissions as a result of human activities, such as transport and infrastructural development are becoming an ever-increasing concern, which consequently has resulted in the anthropogenic climate change problem and on a macro-scale, global warming (IPCC, 2018). Whilst rail is relatively low carbon polluter (Armstrong and Preston, 2011; MacKay, 2009), several studies attempted to bridge the knowledge gap of its operational footprint. These studies formed an important milestone for progress towards more sustainable railway development, targeting further reductions of its emissions and emphasising the case for policies aiming to promote gains in rail patronage (Aditjandra et al., 2012) and thereby reduce the aggregate carbon footprint of today's travel.

A few studies tried to evaluate the whole life carbon footprint associated with the railway industry (RSSB, 2010); while other placed their focus on a route-based analysis (Objectif Carbone, 2009). These studies concluded that the lifecycle phases associated with the infrastructure itself have a significant carbon impact. Estimates suggest that this amounts from 2 (Facanha and Horvath, 2007) to 20% (Milford and Allwood, 2010) of the aggregate railway footprint. This is concluded assuming the total energy consumption over the whole-life of the system ranges from 93 to 160% higher than the operational consumption (Chester, 2008). The Infrastructure Carbon Review (HM Treasury, 2013) suggests that carbon reductions have the potential to yield financial reductions, due to energy demand and material savings on top of delivering operational efficiencies. Carbon reductions can unleash innovation and provide competitive advantages at a business level, all in line with promoting climate change mitigation (HM Treasury, 2013). For example, organisational reforms at the manufacturing stages, may lead to savings in materials and labour, with obvious positive implications in different facets of sustainability. It is worth pointing out that stakeholder engagement and involvement in the carbon reduction process is also important, keeping in mind that these reductions can be achieved only if behavioural changes and revision of the associated processes at a business level occur. The relationship between carbon and Capital Expenditure (CapEx) has been confirmed by Kneifel (2010, 2011).

In the UK, cost overruns continue to grow (ORR, 2022a), with the projected maintenance and renewal expenditure for Control Period[1] 6 (2018/19 – 2023/24) being set at circa £7.5 billion. Despite the fact that financial expenditure is increased, efficiency gains have been hard to realise (McNulty, 2010a). International benchmarking from the Office of Rail and Road (ORR) suggests that in 2008, the efficiency gap in terms of maintenance and renewal expenditure of Network Rail (NR) compared with high-performance European Railways was within a range of 34 – 40% (McNulty, 2010b). Considering this, while renewal levels have been increasing over the past few years in an attempt to deal with a long-standing maintenance backlog; following a steady state analysis, Britain's position has not been particularly favoured (Civity, 2011). Considering the UK's rail network assets, the network comprises of approximately twenty thousand miles of track, the subsequent volume of maintenance and renewal required results in approximately 430,000 to 934,000 annual carbon emissions ($t.CO_2$) (Milford and Allwood, 2010). These facts further emphasise the need for reducing maintenance and renewal needs for the railway infrastructure, to reinstate its position as a transport mode suitable for the challenges of the 21st century.

1.3 Infrastructure Appraisal : looking into the crystal ball?

Life Cycle Assessment (LCA) studies often produce recommendations for strategies to reduce cost of, or emissions from, the study subject in the future, and studies of railway track are no exception to this. Many studies have been undertaken of LCA and Life Cycle Cost Assessment (LCCA) (and variants thereof) for rail infrastructure.

A meta-analysis of 57 railway infrastructure LCA case studies, set the gap of infrastructure embodied emissions at 0.5 to 12,700 tonnes of CO_2 per km (Olugbenga et al., 2019). Factors such as soil characteristics, project type, design, location are some of the root causes for such variations. Statistical analysis by Olugbenga et al. (2019) confirmed that the type of infrastructure and the length of at-grade and tunneling sections have a (statistically) significant impact on these emissions. However, other factors of variability, such as: (i) study goal, (ii) scope, (iii) system boundaries, (iv) functional units, (v) methodology and (vi) data sources, further amplify these variations, and restrict re-usability of these studies to make predictions for future infrastructure projects.

Studies examining the railway system, usually have varying degrees of focus on infrastructure emissions and their reporting, which depends on their goal. This in turn influences the methods selected, scope, boundaries, and the subsequent, data used. The functional unit is another critical factor, as it is intended of serving two functions. First, it should define the

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[1] Control Periods are 5 – year terms into which Network Rail (the owner and operator of most of the railway infrastructure in Great Britain) sets out its priorities for financial investments and upgrades.

purpose of the underlying system or product under investigations and second, it should be appropriately selected, to allow for the normalisation of its impacts, as well as comparisons with competing systems or products that serve or provide similar functions. Immediately, it can be understood that for complex systems, such as the railway infrastructure, the definition of a ’one unit fits all’ becomes somewhat impossible. For example, construction of railway tunnels through different geological conditions, require different quantities of materials and types of excavation processes, which can be masked by employing usage-based functional units, such as VKT[2] or PKT[3], often utilised in High Speed Rail (HSR) studies (Section 2.3). Similarly, such units may obscure construction implications for route choice, when comparing mode alternatives, as for instance, a direct route may lead lengthwise, to less rail infrastructure construction than a more curvaceous route, but use higher material quantities, due to the increased need for tunnels. This will result to less PKT for this route, but the impacts of this trade-off on its functionality will not be captured (Olugbenga et al., 2019). Likewise, distance-based metrics (particularly of project scale), fail to capture the ’section-to-section’ variability of different routes (soil conditions, track design and quality, elevation changes, etc.).

System boundaries are also of high importance both for asserting completeness, and for allowing comparisons to be made between studies. However, this is one of the factors that is highly heterogeneous (Table 2.1) (de Bortoli et al., 2020). Even for studies that do include the same lifecycle phases, there are large variations on what constitutes them, as well as on the degree of focus (level of detail), which results to incomplete assessments and skewed outcomes.

Similarly, the choice of methodology has a direct impact on data requirements, study boundaries, and of course on the final results. Statistical findings by Olugbenga et al. (2019) confirmed this, suggesting that there is a significant impact of the methodology selected on the total embodied emissions calculated for an infrastructure project, with bottom-up LCA methodologies, resulting to lower bound assessments. Whereas, top-down methods (EIO-LCA[4]) having the opposite effect. These methods, depending on their level of detail, have different data requirements. LCA data often come in the form of (i) environmental intensity factors (ii) material and (iii) energy quantities, etc. Traditionally, as the railway system is rather complex, studies in the field tend to rely heavily on secondary data and cross-referencing, with data inputs, often reflecting different geographical boundaries, processes, etc. Moreover, it is common for traditional databases to be employed (see Table 2.5), which inevitably will also skew the results, as for example, technological advances among other factors, will not be captured on the appraisal. Finally, railway LCA studies suffer from the assumption of linearity (Olugbenga et al., 2019), for example, in a railway route, the design of a specific bridge transition, does not necessary reflect the material and fuel quantities of all other transitions on this route. This assumption though is very common in railway infrastructure studies to reduce data requirements and simplify the analysis.

Considering the way the use phase is modelled in LCA studies, maintenance and renewal cycles are often dictated by arbitrarily selected fixed values (Table 2.3) that fundamentally fail to account for the: (i) section-to-section variability, (ii) interactions between components, (iii) correlation between vehicle dynamics and track quality, (iv) difficulty of considering ’*bona-fide*’

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[2] Vehicle-km travelled

[3] Passenger-km travelled

[4] Economic Input-Output Life Cycle Assessment

decision-making, which can vary between Infrastructure Managers (IMs). This fact, restricts the applicability of these models for examining reliably prospective improvements to the system.

1.4 Contribution to Knowledge : on track to the future

LCA studies examining novel track forms, or strategies for achieving cost and carbon improvements, and delivering operational efficiencies are scarce. Of these (limited) applications, the repeated development of bespoke models of study locations, interventions and effects is typical. However, the one-off nature of these models increases both the time and costs necessary, and makes it difficult to compare similar schemes in different locations, or different interventions in a single location (Armstrong et al., 2020). LCA in itself can only be done credibly *ex-post* and with a large amount of information. However, for assessing potential environmental (and economic) improvements over existing systems, appraisal takes place *ex ante* and (usually) with limited information and resources. As a result, feedback on environmental (and economic to an extent) impacts of non-theoretical projects remain fairly rare (de Bortoli et al., 2020; Landgraf and Horvath, 2021).

Therefore, it is understandable that the appraisal of prospective interventions on existing systems becomes somewhat challenging. Considering this, while tests can be carried out on elements of railway track in a laboratory. It is more problematic to apply these results to predict real world field rates of deterioration along the track geometry which is largely a function of differential settlement. This is important, because an understanding of reductions in real world rates of deterioration is necessary to predict (reliably) the performance of such interventions and assess the socio-economic case for altering current practice.

Against this background, the thesis intends to make a significant original contribution to knowledge in terms of both methodology and findings. The intention is for a framework to be developed based on bottom-up principles, having clearly identifiable methodology, system boundaries and functional unit metrics, which will allow for appraisals to be made at different granularity levels (component, asset, route level), depending on the study scope and data availability. The main intention is to create a framework that will be generalised, standardised and highly replicable, qualifying it as a comparison enabling tool for examining potential improvements to the railway track system. This is very important for both stakeholders and academic practitioners as it will: (i) Create new perspectives for targeting lifecycle enhancements; (ii) aid on short and long term policy decisions - technical infrastructure choices, maintenance strategies, etc.; (iii) aid analysis (at different scopes) due to its transferability in terms of location, granularity level, etc. Secondly, it is intended for it to be compatible with different degradation models, so as to transverse from purely static appraisals, moving towards science informed models, based on real world rates of deterioration. This is crucial, because it will allow for reliable predictions to be made on the performance of different track modifications and assess the socio-economic case for altering current practice.

Finally, in terms of findings, the thesis aims at making an original contribution in three different areas. First, the framework will be utilised at the **component level** to assess the performance of the most common sleeper types present in the UK network, and the findings will be compared against those of previous studies, in order to identify and better understand the reasons behind potential variations.

Second, the framework will be extended at the **asset level** and investigate the whole life carbon footprint of a range of different S&Cs used in the UK. The novelty of this analysis lies on the fact that the modelling will be based exclusively on UK network-specific supply chains and production processes, and it will have considerable depth as it will focus on the entire lifecycle of these assets, but also breadth, through examining a large number of both older and newer design variants.

Third, the framework will be combined with an industry-specific asset management model and a method will be proposed to integrate the results of laboratory tests into the model, which will allow for newly introduced interventions to be examined. This will permit the assessment of a range of novel track system modifications from a whole life cost and carbon perspective at the **route level**.

1.5 Research Objectives

The aim of this thesis is to develop an integrated methodology for investigating the potential of a range of novel interventions to reduce the whole life carbon footprint and LCC of ballasted track. This aim will be achieved by meeting the following objectives:

1. Create a detailed lifecycle carbon inventory of selected novel track forms, reflecting UK practice.
2. Investigate the differences between plain track and Switch and Crossing (S&C) layouts in terms of their whole life carbon footprint and carbon costs.
3. Develop a method for using evaluations of the relative benefits of novel interventions from single element laboratory tests to assess whole route performance with respect to their impact on reducing track vertical settlement.
4. Study how track maintenance frequency would be affected by installing novel interventions as standard at renewals.
5. Analyse the implications of novel interventions for LCC and whole life carbon footprint, in order to establish the extent to which these are an improvement over the existing system.
6. Develop and use an improved, more generalised and standardised, transferable, replicable and comparison-enabling approach to the socio-economic assessment of such interventions.

1.6 Thesis Structure

This thesis details how the objectives outlined in Section 1.5 were fulfilled. Following the introduction contained in this Chapter, the remainder of the thesis is structured as follows:

Chapter 2 : reviews the railway infrastructure environmental and economic modelling literature. Particular interest is given on examining factors of variability between studies, such as system and geographical boundaries, infrastructure/asset lifespans, environmental impact categories, functional unit metrics, technical specifications of the track forms, and the modelling/assessment tools used.

Chapter 3 : reviews a range of methodologies (LCA, Carbon footprinting, LCCA, RAMS, CBA, etc.) and extensions of existing models, and the choice of methodology and case studies for the thesis are outlined and explained.

Chapter 4 : is concerned with a modelling framework that has been developed to evaluate the carbon footprint and LCC of ballasted track at the component level. The applicability of this modelling framework is then tested through an exemplar case study. This study examines the whole life carbon footprint and economic performance of the four most common railway sleeper types present in the UK railway network.

Chapter 5 : extends the capability of the modelling framework presented in Chapter 4, moving from the component to the asset level, as well as diverting from plain track to more complex layouts (i.e. S&Cs). The proposed modelling framework is then tested through a novel case study. This case study examines the whole life carbon footprint and carbon costs of the most common S&C design variants present in the UK railway network, as identified by asset population data supplied by NR.

Chapter 6 : starts by proposing a method for incorporating the improvement in overall settlement found in laboratory test results into an existing industry – based asset management model (Vehicle Track Interaction Strategic Model (VTISM)) to evaluating whole route performance. Chapter 6 then discusses the development of a modelling framework (implemented in Python) for evaluating the implications of installing different interventions to ballasted track at the route level, in order to establish the extent to which these are an improvement over existing systems.

The proposed framework links outputs from VTISM with a cost and carbon inventory to model the LCC and whole life carbon footprint of different track interventions and compare them against the base case. Outputs from the model are in the form of financial NPV, IRR, Carbon Costs, and Payback Period. Finally, Chapter 6 outlines the results from a socio-economic assessment of installing seven different novel track forms on two different UK routes.

Chapter 7 : concludes the thesis by summarising its findings and outlines some potential areas for future work.

Chapter 2

Literature Review

2.1 Introduction

This chapter contains a literature review in the field of socio-economic modelling of railway infrastructure. Section 2.2 presents a comprehensive review of studies in the field of railway environmental modelling. Section 2.3 describes the importance of Functional Unit(s) (FU) and discusses the impact that these may have in LCA studies. The chapter then continues on describing (Section 2.4) the importance of system and geographical boundaries in LCA studies. Section 2.5 partitions the lifecycle of railway infrastructure into its constitutive phases and briefly discusses these in relation to their whole-life carbon modelling. Section 2.6 reviews a range of alternative infrastructure emission reduction strategies. This section continues with a review of environmental modelling studies of more complex track layouts, as well as of alternatives to the conventional ballasted track. Section 2.7 outlines some of the tools available for carrying out a LCA. The chapter continues with a discussion on the economic literature of railway infrastructure, with a particular focus on LCCA (Section 2.8). Section 2.9 examines a UK industry – based asset management tool that has been developed to support infrastructure cost modelling. The chapter then concludes (Section 2.10) by outlining the gaps in the literature, and describes the anticipated contributions to knowledge of the thesis.

The objective of this chapter is to provide a thorough review of previous case study applications in the field of railway environmental and economic modelling and explore further their limitations and weaknesses, which will allow the identification of areas where potential improvements can be made. Therefore, the expected outcome of this chapter is to establish the gaps in knowledge and make an initial selection of the methods (and modelling assumptions) and case study candidates for this thesis.

2.2 LCA for rail infrastructure

2.2.1 Railway operations

The majority of the railway transport environmental impact analysis focuses on the emissions from vehicle operation, better known as 'direct' or 'tailpipe' emissions (see Bergin et al. (2009)). Generally, these studies (ATOC, 2007; Baron et al., 2011), conclude that rail has better environmental performance, with lower CO_2 emissions per passenger kilometre compared with other land-based modes of travel. Ortega et al. (2018a) described the reasons for the favourable position of rail. They posit that when comparing the EU road vehicle weight limits to freight trains, the ratio is approximately 1:40[1] (Mayer et al., 2012). Nevertheless, overall efficiency gains (in terms of financial, environmental and accident costs) have been reported in European countries, where these limits have been relaxed (permitting the use of longer and heavier road vehicles) (Ortega et al., 2014). In addition, when rolling resistance comes into play, comparing the wheel to rail interface (predominantly steel to steel interaction) with that of rubber on tarmac, the energy requirements to transport a given weight by rail is lower than for road (Ortega et al., 2018a). Additionally, in many countries railway vehicles are powered by electricity, rather than diesel which is the main operating fuel for road vehicles (Mayer et al., 2012). This fact reinforces further the dominant position of rail over other land-based alternatives. However, the electricity mix during the production stage is the true indicator of how sustainable this power generation source is in reality. Nevertheless, when road transport is concerned, its unique characteristic of door-to-door service provision is hardly matched by other transport modes. Thus, on average intermodal shipment operations constitute a good option for improving carbon efficiency, although such savings are complex to forecast, and have a high variation depending on the examined route (Craig et al., 2013). Another option is to use a Geographical Information System (GIS) based spatial model of rail and road networks (Zuo et al., 2013). Based on this, several spatial policy scenarios have been tested to examine imbalances between inter-regional flows of minerals across England and Wales. The provision of new links between quarries and railway lines was found to have positive implications on reducing CO_2 through a potential shift from road to rail. However, It was suggested that this could only be viable for quarries within a close proximity to the existing network, as the investment required is large, and perhaps a better option may be the introduction of new technologies to improve the road fleet efficiency (Zuo et al., 2013).

Similar observations have been made for the US Conventional Railway (CR) system, where the air pollutant emissions, Greenhouse Gases (GHG) and energy consumption have been found to be lower than for road and air freight (Facanha and Horvath, 2006, 2007; Chester and Horvath, 2009). However, for passenger rail, the dependence of the US on coal-powered electric vehicles, as well as the refining of diesel and gasoline fuels (sulphur removal), results in relatively high SO_2 emissions (Facanha and Horvath, 2006, 2007; Chester and Horvath, 2009). Similarly, in the UK, diesel is the predominant source of energy used by the rail industry to power vehicles. However, large investments have been planned for the electrification of selected routes (Network Rail, 2013), as only 40% of the network is currently electrified (Esters and Marinov, 2014).

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[1] A freight train has a carrying capacity of c. 2000 tonnes, which translates approximately to that of 40 freight trucks (Mayer et al., 2012).

When it comes to passenger traffic, the magnitude of rail emissions and its advantage over other modes is dependent on the levels of occupancy (Álvarez, 2010; Chester and Horvath, 2009, 2010; Chester et al., 2010, 2013; Pritchard et al., 2015). Álvarez (2010) evaluated the tailpipe emissions and energy consumption of high speed trains and compared them to that of conventional trains. He found the energy consumption per passenger to be 29% lower for the Spanish High Speed Rail (HSR). Ortega et al. (2018a) and Álvarez (2010) suggest that this is related to the more homogeneous speed profile, enhanced load factors, less curves and stops, and that the HSR traction is primarily powered by electricity rather than diesel, as well as the route coverage for HSR, which is often less than for CR for competing routes. Esters and Marinov (2014) found a proportional relationship between the square of speed and energy consumption, suggesting that HSR (electric) traction is more carbon intensive compared with conventional (diesel or electric) trains at maximum operating speeds. The difference between these studies is due to a range of factors being omitted from the latter study, such as the (i) distance travelled, (ii) inertial/grade resistance, and (iii) the UK energy mix. Additionally, rail modes may have the smallest proportion of operational to aggregate energy use because of their low fuel requirements per passenger relative to the total emissions by the supporting infrastructure (Chester and Horvath, 2009).

2.2.2 High speed rail

Many LCA studies of railway infrastructure have been undertaken, focusing on its absolute environmental impact. Some studies (Lee et al., 2008; Spielmann and Scholz, 2005; Tuchschmid, 2009; von Rozycki et al., 2003) have attempted a full LCA of ballasted or ballastless track. However, due to the complexity of carrying out such analysis, they display a high variation to the extent that the necessary factors are adequately covered.

For example, von Rozycki et al. (2003) examined the environmental impact of the German HS line between Hannover and Würzburg. However, they did not consider the emissions arising from maintenance and decommissioning. Another study by Lee et al. (2008) evaluated the environmental impact of ballasted and concrete South Korean HS lines using a partial LCA. Their analysis was effectively a cradle-to-gate as they omitted the decommissioning phase and only included a very crude estimate of maintenance emissions. Similarly, a study of the emissions of HSR infrastructure in Europe only considered the construction phase (Tuchschmid, 2009).

Looking at the embedded carbon of the HSR infrastructure for the construction and decommissioning phases, the heavy use of carbon intensive materials such as steel and concrete makes these emissions account for a significant share of the total footprint (Andrade and D'Agosto, 2016; Chester and Horvath, 2010; García, 2011; Network Rail, 2009).

Kaewunruen et al. (2019) conducted a LCA of the Beijing-Shanghai HSL. They found that the majority of the CO_2 emissions and energy consumption stem from the construction of the infrastructure, accounting for about 64.9% and 54.3% respectively. This was also confirmed by a LCA by Grossrieder (2011) targeting the projected High Speed Line (HSL) between Oslo and Trondheim in Norway. She concluded that the infrastructure is the main contributor to the total carbon emissions (87.8%), whereas rolling stock (0.68%) and operational emissions (11.52%) had considerably smaller contribution to the overall footprint (Grossrieder, 2011). It was suggested that the high carbon share of the infrastructure stems from the high volume of steel, cement and extruded polystyrene used during construction (Grossrieder, 2011). While for the case of the operational emissions, the clean electricity mix used in Norway in conjunction with the low levels of service frequency, were the primary factors for the low CO_2 share (Grossrieder, 2011). Another study by Société Nationale des Chemins de fer Français (French National Railway Company) (SNCF) of the Rhine–Rhone HSL (making use of factors from ADEME to estimate the Emission Factors (EFs) for different elements of the production process) found that the largest source of construction emissions came from the use of lime for ground treatment (c. 33%) (Objectif Carbone, 2009). This study makes use of a proprietary process termed as Bilan Carbone®. However, this does not appear to differentiate from conventional LCA frameworks, except that it explicitly outlines priorities for emission reduction.

Bueno et al. (2017) examined the environmental performance of the Basque Y[2] HSR infrastructure in Spain. They found a high initial environmental deficit (2.71 $MtCO_2$) attributed to its construction/maintenance, leading to small Net Savings (NS) at the end of its lifetime. In relative terms, this is quite sizeable compared to other HSR lines (see Baron et al. (2011); Chang and Kendall (2011); Chester and Horvath (2010); von Rozycki et al. (2003); Yue et al. (2015)), relative to its length and electricity-mix, particularly when compared with HSR projects in China (see Baron et al. (2011); Yue et al. (2015)). This can be explained by the mountainous orography of the region leaving only 30% of the track in open air, with the remaining layout running through 23 tunnels (60%) and 44 viaducts (10%) (Bueno et al., 2017). Nevertheless, these results may be a product of different factors such as: (i) the scarce annual passenger demand of 2.45 mil., which is miniscule (c. 6.3 – 19.2 times less) compared to that of similar studies (see Åkerman (2011); Baron et al. (2011); Chang and Kendall (2011); Chester and Horvath (2010); von Rozycki et al. (2003); Yue et al. (2015)), leading to 7.5 – 20 times greater gCO_2 per passenger-km travelled (PKT), (ii) the high induced demand, which is a critical input as cited by other authors (see Åkerman (2011); Bueno et al. (2017); Burgess (2011); Chen et al. (2016); Cheng (2010); Hensher et al. (2012); Hsu et al. (2010); Lynch (1990)), and (iii) the relatively modest modal shift from road and air (Bueno et al., 2017).

It is worth pointing out that there is no universal agreement on the environmental impact of rail infrastructure when compared with that of road construction, with Facanha and Horvath (2007) positing that the construction of rail infrastructure is less carbon intensive than that of road, when looking at the tonnes per freight mile transported over the infrastructure's lifecycle.

2.2.3 Bridges, tunnels and aerial structures

Considering civil engineering structures such as bridges, viaducts and tunnels, their heavy embedded carbon can outweigh their operational benefits associated with reductions in gradient requirements (Pritchard, 2015; Pritchard and Preston, 2016). However, pursuing reductions of embedded carbon by minimising the tunnel diameter can bring about as many disbenefits as benefits, meaning, that due to the enhanced air-resistance the associated operating energy consumption will be increased (Pritchard and Preston, 2016). Pritchard and

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[2] 180km high speed rail network connecting the three capitals of the Basque Country: Bilbao, Vitoria-Gasteiz and Donostia-San Sebastián.

Preston (2016) suggest that the magnitude of this increase is proportional to the diameter of the tunnel relative to the size of the train. A key point from their work is that for a given railway project, an optimum tunnel diameter will exist to balance both operational and infrastructural emissions (Pritchard and Preston, 2018). This balance depends on different factors such as the train running speed, station placement, intensity of usage, as well as factors related to the design of the tunnel itself that affect air pressure and resistance (Pritchard and Preston, 2016, 2018).

To get a better sense of the magnitude of these emissions, Chang and Kendall (2011) showed that on the projected HSL in California, aerial structures and tunnels would account for 60% of the total carbon emissions, while lengthwise they represent only 15% of the planned lines. Network Rail (2009) posit that for open sections the embedded emissions per annum display a variation between 140 – 230 tonnes of $CO_{2eq.}$ per track km (depending on type and rate of recycling), while, for tunnels the equivalent figure is approximately 880 – 980 tonnes. A study of the Austrian railway network by Landgraf and Horvath (2021) found the GHG emissions per km year of tunnels made of concrete to be sixteen times higher than for open sections. Westin and Kågeson (2012) analysed the trade-off in a 500 km double track HSL with 10% tunnels. Considering a central scenario, they estimate about 14 million one-way trips per annum are necessary to offset its embedded emissions, split into 45% from other modes, 30% from existing rail users and 25% newly generated traffic. However, from a socio-economic lens, some studies set the first-year operational threshold to be above 8 to 10 million passengers (de Rus and Nombela, 2007; de Rus, 2008, 2012), with only certain circumstances suggesting a bare minimum of 6 million passengers (low discount rate and construction costs, along with high value travel time savings) (Barrón et al., 2012; de Rus and Nash, 2007).

Banar and Özdemir (2015) assessed the economic and environmental performance of the Turkish HSR and CR systems using a combination of LCC and LCA methodologies. They found a split between infrastructural and operational emissions of 58% and 42% respectively. This gap was even greater for CR, but tipping the scales towards a higher operational load.

Baron et al. (2011) found in their study the Asian HSLs (i.e. Taiwan and China) to have a carbon footprint as much as five times greater than for the lines in South Europe. For example, the HSR line running between Taipei and Kaohsiung emitted around 176.5 tonnes of CO_2 per km per annum compared to an equivalent 68 tonnes for the French LGV Méditerranée HSL. This performance-gap may be explained by the imposed space constraints during construction (i.e. for the former case only 9% of the line is open track) and by the operational emissions stemming from the electricity mix (i.e. coal-based in China) of each country (Yue et al., 2015). Similar reasons were observed for the Turkish HSR and CR, where their infrastructure heavily depends on bridges to cross diverse terrain and their electricity mix is mostly based on fossil fuels (Baron et al., 2011).

Milford and Allwood (2010) assessed the CO_2 impact of the three core phases of the LCA, namely, construction, maintenance and End-of-life (EoL) of all the main track components used in the UK. They developed a spreadsheet model using a streamlined LCA methodology. Chester (2008) adopted a more generalised methodology using a hybrid LCA for creating a Life Cycle Inventory (LCI) of the passenger transport in the US, including appraisal of five different rail systems. His analysis appears more comprehensive as infrastructure was considered alongside fuel consumption and vehicles.

It must be pointed out, that an LCA should be always complemented by a form of economic appraisal as albeit the considerable environmental benefits some railway projects may yield, they may well be unsuitable in socio-economic terms. A good example is the commuter rail system of Montreal, Quebec where the main production source for electricity comes from hydropower at a relatively low cost. As a result, the environmental benefits of complete electrification of the system or use of fuel cell vehicles are high (i.e. approximately 98% emissions reduction per annum) and the costs of operation are also low (Chan et al., 2013). However, the complementary infrastructure required for this scheme in absence of any significant demand, makes the investment unfeasible in financial terms. Another study targeting the California HSR and three urban projects, confirmed that when different schemes are being compared in terms of carbon benefits in monetary units, the risk of getting misleading results is heavily dependent on the selected assumptions and methodology (Matute and Chester, 2015).

2.3 The importance of choosing a metric

Considering the metric units used to quantify infrastructure impacts, there is an evident variation between studies, which can make comparisons between them difficult.

A number of authors present their findings in passenger-km travelled (PKT) (Bueno et al., 2017; Chang and Kendall, 2011; Chester and Cano, 2016; Chester and Horvath, 2009, 2010, 2012; Chester et al., 2010; Cueno, 2016; Jones et al., 2017; Lederer et al., 2016; Li et al., 2018; Miyoshi and Givoni, 2014; Network Rail, 2009; Shinde et al., 2018; von Rozycki et al., 2003; Westin and Kågeson, 2012; Yue et al., 2015), passenger-mile travelled (PMT) (Chester et al., 2012, 2013), vehicle-km travelled (VKT) (Chester and Horvath, 2009, 2010, 2012; Chester et al., 2010; Li et al., 2018), or track-mile travelled (TMT) (Hanson et al., 2016). This (attributional) approach appraises the long-term (average) impacts of each system by allocating them to, for example, a PKT. This allows for a potential comparison between infrastructure and operational emissions, as the latter are usually expressed in this metric (see Tuchschmid (2009); von Rozycki et al. (2003), etc.). However, it is often difficult to normalise under this metric, as it requires some knowledge of the passenger occupancy levels.

This highlights another complexity, as factors such as traffic density are often being overlooked. Traffic density itself can pose a considerable impact on the carbon efficiency of a railway route. This is often the case when route-based comparisons are concerned, as the traffic density will not only impact the service life of track components but also increase the maintenance requirements in response to increasing traffic levels. Additionally, this metric is also useful as it allows comparisons with other transport modes. Comparisons such as these regularly favour rail over other transport modes. However, it is often observed that the associated infrastructure is not accounted for, and attention is only placed on the tailpipe emissions.

Another issue with this approach is that it requires "the selection of a normative future to assess each mode at a comparative time period when ridership, vehicle technology, and electricity mix changes have aligned around policy informative conditions" (Chester and Cano, 2016). Thus, its outputs are useful for assessing performance as a snapshot in time.

Consequently, although it provides "some indication of how relative performance changes, it masks the timeliness in which impacts occur" (Chester and Cano, 2016). This is because the PKT metric spreads these impacts over a specific operation lifecycle, showing all impacts that can be attributed to each mode, and does not differentiate between the lifecycle processes that are affected from the implementation of different transport policy decisions (Chester and Cano, 2016).

Fundamentally, these time-independent approaches capture (averaged) environmental impacts and energy at some period in the future, making the appraisal of any temporal (marginal) variations of impacts at a given year unclear. Nevertheless, these results are still useful for informing decisions on ways to reduce environmental impacts and energy use in different lifecycle processes (by identifying infrastructure 'hotspots') (Chester and Cano, 2016).

In response to this, Chester and Cano (2016) proposed a marginal (consequential) approach so as to allow for the year-on-year variations in lifecycle emissions to be accounted for. This led to any uncertainties related to the selection of a normative future to be avoided. It has been suggested that this approach would be viable and often superior for incorporating lifecycle results into transportation policy-making or as a basis for project selection in financing programs, etc. (Chester and Cano, 2016).

Another study by Milford and Allwood (2010) present their finding in terms of embedded emissions (or energy) per length of track per year. This effectively allows summation of impacts of track components with different service lives. Therefore, the true carbon impact of different track components can be assessed by accounting their lifespan, allowing comparisons between them. The lifespan is of great importance as, for example, during the construction stage of slab track the concrete subbase and foundation may appear to have the highest impact. However, when their lifespan is considered, the most carbon sensitive components appear to be the rails due to their considerably lower service life. This effectively means that the embedded emissions of rails are averaged over a shorter service life. While this metric does not require any knowledge of the associated usage of the infrastructure, it makes comparisons with operational aspects of the system virtually impossible.

Peters et al. (2011) suggested that the way time is treated along with the emission metrics adopted can have a great influence on LCA. It is perhaps more clear that when time is concerned, a diverse range of values can be evaluated for the same effect in relation to the year it is accounted for, the lifecycle adopted or the lifespan of the track itself (Krezo et al., 2016). Peters et al. (2011) proposed the choice of metrics to be made in relation to each examined impact, whereas the time scales may be defined in accordance to the goal and scope of the study.

2.4 The importance of scope and boundaries

A large number of railway LCAs have been carried out by both researchers and consultants. System and geographical boundaries of the rail infrastructure are some factors of considerable variability (Table 2.1). The selection of System Boundary (SB) is particularly important (discussed in section 3.3.1.1) as a potential harmonisation across studies will allow comparisons to be made, and also for past models to be useful for future predictions

(Olugbenga et al., 2019). A common observation across the reviewed studies is that the stage of EoL is omitted. Similarly, maintenance/renewal is either addressed superficially or only replacement of individual components is considered. Additionally, for the studies that do include maintenance, there are large variations on what constitutes these (intervention) actions.

TABLE 2.1: Selection of SBs from selected publications (adapted after Olugbenga et al. (2019)).

Reference	System	Sub-system				System Boundary			
		Track	Stations	Bridges	Tunnels	Construction	Operation	Maintenance	EoL
Ueda et al. (1999, 2003)	HSR	✓				✓		✓	
von Rozycki et al. (2003)	HSR	✓	✓	✓	✓	✓	✓	✓	
Facanha and Horvath (2006)	F	✓				✓	✓	✓	
Chester (2008)	HRT, C, M, LRT, HSR	✓	✓			✓	✓	✓	
Kiani et al. (2008)	C	✓				✓		✓	
Crawford (2009)	C	✓				✓		✓	✓
Chester and Horvath (2009)	HRT, C, M, LRT, HSR	✓	✓			✓	✓	✓	
Tuchschmid (2009)	HSR	✓	✓			✓	✓		
Network Rail (2009)	I	✓	✓		✓	✓	✓	✓	✓
Schmied and Mottschall (2010)	C, F	✓		✓	✓	✓	✓	✓	
Chester and Horvath (2010)	HSR	✓	✓			✓	✓	✓	
Chester et al. (2010)	C, M (?)	✓	✓			✓	✓	✓	
Stripple and Uppenberg (2010)	HSR	✓	✓	✓	✓	✓	✓	✓	
Milford and Allwood (2010)	C	✓				✓		✓	✓
Grossrieder (2011)	HSR	✓		✓	✓	✓			
Åkerman (2011)	HSR	✓	✓	✓	✓	✓	✓	✓	
Asplan Viak AS (2011)	HSR	✓	✓		✓	✓	✓	✓	✓
Jehanno et al. (2011) [1]	HSR								
Tuchschmid et al. (2011) [1]	Various	✓	✓	✓	✓	✓		✓	
Baron et al. (2011)	HSR	✓	✓	✓	✓	✓			
Chang and Kendall (2011)	HSR	✓			✓	✓			
Westin and Kågeson (2012)	HSR	✓	✓		✓	✓	✓	✓	
Chester and Horvath (2012)	HSR	✓	✓			✓	✓	✓	
Chester et al. (2012)	LRT	✓	✓			✓	✓	✓	
Chester et al. (2013)	LRT	✓	✓			✓	✓	✓	
Morita et al. (2013)	LRT	✓	✓		✓	✓	✓	✓	
Bolin and Smith (2013)	C	✓				✓		✓	✓
Miyoshi and Givoni (2014)	HSR	✓	✓		✓	✓	✓	✓	
Yue et al. (2015)	HSR	✓	✓	✓	✓	✓			
Banar and Özdemir (2015)	HSR, C	✓		✓	✓	✓	✓	✓	✓
Matute and Chester (2015)	LRT, HSR	✓	✓			✓	✓	✓	
Chester and Cano (2016)	LRT	✓	✓	✓		✓	✓	✓	
Cueno (2016)	HSR	✓	✓	✓	✓	✓	✓	✓	
	I	✓	✓	✓		✓	✓	✓	
	F	✓	✓	✓	✓	✓	✓	✓	
Hanson et al. (2016)	C	✓		✓	✓	✓			
Lederer et al. (2016)	LRT	✓	✓			✓	✓	✓	
Bueno et al. (2017)	HSR	✓	✓		✓	✓	✓	✓	
Saxe et al. (2017)	M	✓	✓		✓	✓	✓	✓	
Jones et al. (2017)	HSR	✓	✓			✓	✓	✓	
Shinde et al. (2018)	C	✓	✓			✓	✓	✓	
Li et al. (2018)	M	✓	✓		✓	✓	✓	✓	✓
Ortega et al. (2018a)	I, C	✓						✓	
Chang et al. (2019)	HSR	✓		✓	✓	✓	✓		
Fridell et al. (2019)	F	✓			✓	✓	✓	✓	
de Bortoli et al. (2020)	HSR	✓		✓		✓		✓	✓
Cheng et al. (2020)	HSR	✓	✓	✓	✓	✓			
Lee et al. (2020)	HSR	✓	✓	✓	✓	✓			
Landgraf and Horvath (2021)	C	✓	✓	✓	✓	✓	✓	✓	✓

[1] Meta-analysis.

2.5 Railway Infrastructure Carbon Footprint

2.5.1 Track components and construction

2.5.1.1 Track components

When an LCA of railway track-related emissions is carried out, it is not sufficient to treat the railway track as a single entity, as in reality it is comprised of a number of heterogeneous components, each having inherently a very diverse range of characteristics. Therefore, the level of detail is of great significance and system disaggregation may be necessary. Often studies focusing on the quantification of the economic/environmental impacts of the railway track system may be invalid as they are failing to model it at a reasonable level of detail. However, it may be difficult to model the system in its entirety as the precise mix of components will vary between different track designs.

One of the most comprehensive studies identified in terms of level of detail is by Milford and Allwood (2010). They used NR GeoGIS Infrastructure database to identify the primary types of track components in UK rail network. The track components considered in their model included the following: (i) rails, (ii) sleepers, (iii) fastenings, (iv) baseplates, (v) ballast, (vi) fixings, (vii) fishplates, (viii) geotextile separator, (ix) sand blanket. However, as already discussed further disaggregation may be necessary, for example, Milford and Allwood (2010) used a range of options for varying proportions of recycled material within the rail section. As discussed earlier, the service lives of track components will also affect their lifecycle emissions. Considering this, Milford and Allwood (2010) calculated these based on values extracted from VTISM. Another study by Kiani et al. (2008) adopted the service lives and material quantities through Delphi surveys.

2.5.1.2 Component Processing

Installation procedures, including tasks such as rail welding, cutting, ballast spreading among others will also generate emissions. However, specific estimates of such figures are scarce. Milford and Allwood (2010) suggest that these emissions typically contribute less than 8% of the overall emissions.

2.5.1.3 Component Transport

Emissions will also be generated from the transportation of materials and components associated with the construction, maintenance and renewal processes. Such emissions are highly site-specific, as they depend on the distance from the material source (gate) to the site, but also on the modes utilised. Milford and Allwood (2010) assumed an arbitrary transport distance of 200 km for all components using rail freight, based on this assumption, they estimated these emissions using Department for Environment, Food and Rural Affairs (DEFRA) EFs. Milford and Allwood (2010) argued that even with an arbitrarily selected distance of this magnitude, construction transport typically accounts for less than 3% of the overall emissions. Similarly, Ortega et al. (2018a) assumed a general source-to-site distance for all components and maintenance staff of 50 km by rail. They then estimated these emissions using data from the Arup database CO2ST. Following a sensitivity analysis, they found that the change of emissions to travel distance was very low for both routes examined (0.572 to 0.864 CO_2 t/km).

2.5.2 Track Maintenance

Many railway infrastructure studies often omit emissions resulting from track maintenance, and even in some studies which attempt to estimate these emissions, there is often little detail of what is considered as forming part of such maintenance.

Milford and Allwood (2010) estimated these emissions from three main activities carried out on ballasted track (ballast tamping[3], stoneblowing[4] and rail grinding[5]). The maintenance frequencies adopted were based on estimates provided by NR, with the subsequent emissions being modelled indirectly based on the vehicles fuel consumptions. Chester (2008) calculated these emissions (from material replacement, inspection and rail grinding) based on the labour productivity and equipment utilised, as well as using rail maintenance EFs from the SimaPro software. Krezo et al. (2016) found that the emissions from renewal and maintenance interventions are dominated by the embedded carbon (90 – 98%) from the materials used, with the machinery being responsible for the remaining percentage.

Ortega et al. (2018a) estimated maintenance machinery emissions, using identical construction speeds as in Kiani et al. (2008), assuming an eight hour shift per intervention. They then made estimates of these emissions using values from the Arup carbon database CO2ST, with the intervention cycles being estimated using proprietary rail industry software VTISM. For interventions with variable requirements (stoneblowing and rail grinding), the authors assumed the same proportion of emissions with respect to tamping (2.73 and 6.54 times) as did Milford and Allwood (2010). Such approach seems logical, as for example, while stoneblowers can have the same operational speed as tamping machines (Zaremsbki and Newman, 2008), the quantity of ballast added per intervention is case specific (McMichael and McNaughton, 2003). Similarly, traxcavation emissions may also be highly variable, as they will be dependent on the quantity and type of soil to be excavated.

Network Rail (2009) were unable to identify information which would allow them to compare the maintenance emissions from ballasted and slab track. However, they noted that such a comparison would be beneficial as the main benefits of slab track might be expected to arise from its reduced maintenance requirements, making it more energy efficient over long timescales (Kiani et al., 2008). Besides maintenance emissions, non-maintenance operating emissions from heating of electric rail points during winter are major energy active components and may need to be considered in a rail infrastructure LCA (von Rozycki et al., 2003).

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[3] Tamping is a process which consists of lifting the track and squeezing the ballast under the sleepers to fill the space generated.

[4] Stoneblowing is a process which consists of lifting the track and inserting fresh stones between the sleeper and the surface of the ballast layer, without modifying its compaction state.

[5] Rail grinding is a process which consists of restoring the rail profile and removing irregularities from worn track.

2.5.3 End-of-life

Appraisal of the EoL pathway of the infrastructure when it becomes life-expired is often disregarded in railway LCA studies (see Table 2.1). Milford and Allwood (2010) posit that these emissions are predominantly transport-related. However, the processes of dismantling, incineration and landfilling will also generate a sizeable portion of emissions. Nevertheless, most of the existing studies largely omit this stage due to scarcity of process-specific information related to the exact pathway of infrastructural components.

2.6 Infrastructure emission reduction strategies

2.6.1 Rails

Looking at alternative emission reduction strategies, Milford and Allwood (2010) found the rail section to be the component benefitting the most from a potential service life extension. They tested a number of different rail and track designs, with the double-headed conventional track performing the best. Its main benefit was the effective service life extension of the rail section without any significant gains in its mass. They suggested that if the whole track system was to be replaced by this design, up to 40% reduction in annual emissions from the railway track could be realised. It should be pointed out that this was the purpose of the double sided bull head rail which dominated the UK rail network from the mid nineteenth century until the mid 1950s. It never proved possible to use the second side as the underside also wore where it had been secured to the sleeper (Connor, 2017). Other alternatives for extending the service life of rails and decreasing maintenance requirements include the development of new more durable steel grades. For example, bainitic or pearlitic steels.

2.6.2 Ballast

Bressi et al. (2018a) conducted a LCA to quantify the environmental impacts of using Bitumen Stabilised Ballast bound with bitumen emulsion (BSB) and compared its use with traditional ballast. They found that the use of BSB reduced the environmental impact of the infrastructure through its higher durability, which allowed for reductions in element replacement frequency and improvements in track quality. It was also found to be economically viable in terms of its LCC when compared with conventional ballasted track (Giunta et al., 2018). Another study by Bressi et al. (2018b) examined the environmental performance of different alternative bituminous sub-ballast mixtures containing recycled materials, i.e. Reclaimed Asphalt Pavements (RAP), Crumb Rubber Modified mixture (CRM) and compared their use to that of traditional bituminous sub-ballast. They showed that the CRM variant exhibited higher negative impacts compared to the traditional mixture owing to the processes of rubber treatment as well as the higher amounts of bitumen employed in this mixture. However, when RAP was used there were some considerable environmental improvements. These were magnified when a full blending of virgin and reclaimed binder was assumed, allowing for a reduction in the amount of the former in the mixture.

2.6.3 Sleepers

One area which has proven particularly controversial is the question of which sleeper material minimises whole-life CO_2 emissions (Table 2.2), as wood tends to be viewed as being less carbon-intensive material than concrete. For example, two studies targeting the appraisal of different sleepers used in the Japanese Shinkansen system concluded that timber sleepers have marginally lower emissions compared to concrete, with steel and synthetic sleepers performing the worst (Ueda et al., 2003, 1999). Another study conducted by Werner (2008), concluded that timber sleepers (e.g. beech and oak wood) result in considerably less GHG emissions compared to the ones made of concrete and steel. Conversely, Milford and Allwood (2010) suggested that replacing all timber and steel sleepers on the UK railway network with concrete sleepers could yield 6 – 9% less CO_2 emissions. Similarly, an assessment of the reinforced concrete and timber sleepers for the Australian network over a 100-year lifecycle, revealed that concrete sleepers (30 – 50 year service life) produce 70% less CO_2 compared to the best timber sleeper scenario examined (30-year service life with 96% reuse of steel fastenings) (Crawford, 2009). Nevertheless, Owens (1997) showed that timber sleepers are more environment-friendly than concrete sleepers due to the reduction in carbon emissions. The difference between these results is mainly explained by the figures used to evaluate the amount of storage of carbon and carbon dioxide in timber sleepers. Similarly, Bolin and Smith (2013), concluded that creosote impregnated sleepers offer better environmental performance in terms of fossil fuel and water use, and lower environmental impacts compared to Plastic Composite (P/C) or concrete sleepers. With the exception of the eutrophication impact for P/C sleepers, all impacts were found to be favourable to timber sleepers. The methodology used consisted of a cradle-to-grave LCA underpinned with a gravity analysis to identify the most influential processes, and both uncertainty and sensitivity analysis of the results.

TABLE 2.2: Comparison of the environmental profile of different sleepers from selected studies. [✓✓✓or ✓✓]: best performance, [✓]: better performance, [✗]: worse performance, [?]: not appraised.
Source: Rempelos et al. (2020b)

Study	Concrete	Timber[1]	Steel	P/C[2]	Country
Künniger and Richter (1998)	✓✓	✗	✓	?	Switzerland
Ueda et al. (1999, 2003)	✓✓	✓✓✓	✓	✗	Japan
Owens (1997)	✗	✓	?	?	Australia
Werner (2008)	✗	✓✓	✓	?	Germany/Switzerland
Crawford (2009)	✓	✗	?	?	Australia
Milford and Allwood (2010)	✓✓	✓	✗	?	United Kingdom
Bolin and Smith (2013)	✗	✓✓	?	✓	United States
Landgraf and Horvath (2021)	✓	✗	?	?	Austria

[1] Hardwood or softwood.

[2] Plastic Composite.

Considering the environmental impact of wooden sleepers made of beech compared to ones made of oak, Werner (2008) suggested that their impacts do not vary considerably, as the marginally lower oven dry weight of the oak sleepers and their lower creosote insertion rate is being compensated with a lower heating value per sleeper, which translates to a lower fuel substitution effect as a result of the thermal utilisation and heat recovery of wood.

Dolci et al. (2020) evaluated the environmental performance of a new type of sleeper (i.e. Greenrail) comprised of an inner core made of pre-stressed concrete wrapped by an outer shell manufactured with end-of-life tyre powder and recycled plastics. They then compared its performance against that of traditional concrete sleepers for different operational conditions. Dolci et al. (2020) found that for the worst operating conditions, the differences between the lifecycle environmental impacts of the two sleepers are insignificant. However, for the best scenario, results favour the GR 260 WHS sleeper, which achieved reductions of 20 to 30% for 11 (out of the 16) impact categories examined.

The differences in conclusions from these studies arise due to a series of factors: (i) the mass of components is different between each study due to the different design characteristics being used in each country, (ii) the service lives assumed vary between studies (Table 2.3), (iii) the Carbon Factors (CFs) display a variation between studies as they are drawn from different sources (Table 2.4), (iv) the methodological framework and the subsequent modelling choices largely differ between studies.

Considering the service lives selected, these can have a major influence to the results of such studies, as they determine the amount of interventions required over a studied period. For example, timber sleepers, were found to have a variation ranging from 10 to 45 years, suggesting that their CO_2 emissions when normalised on a per sleeper year basis can vary by as much as 4.5 times. Similarly, the selection of CFs has a large impact to the outcomes of these studies, for example, *ceteris paribus*, the use of the hardwood sleeper CF by Crawford (2009) as opposed to the one by Milford and Allwood (2010) will result to seven times more CO_2 per hardwood sleeper installation. Adding to this, when considering the component mass and spacing differences between studies, these emissions variations may be set further apart.

Crawford (2009) identified a number of strategies for reducing CO_2 emissions from railway sleepers: (i) sleeper size reduction, (ii) making use of steel with less primary material (i.e. higher recycled content), (iii) incinerating phased out timber sleepers for electricity production, (iv) and even achieving material intensity reduction (i.e. displacing cement with up to 50% fly ash). RSSB (2010) recommended that emission reductions can be achieved through the substitution of the cementitious material used for concrete with blast furnace slag or fly ash. Chester and Horvath (2009) concluded that a potential reduction in the use of concrete or a switch to lower energy input and GHG-intensity materials would enhance the performance of railway infrastructure.

2.6.4 Optimising Component Combinations

Ortega et al. (2018a) suggested that a reduction in the use of concrete and steel components, and maintenance machinery through reduced renewal needs can be an attractive option on reducing both costs and CO_2 emissions. Nevertheless, from a strategic planning perspective, a better option would be to combine track components with similar service life, preventing the need to remove functional components prior life expiration (Milford and Allwood, 2010). This will also generate additional (indirect) benefits in terms of improved line availability (avoid replacing individual components at different times) (Milford and Allwood, 2010).

TABLE 2.3: Service life of railway track components from selected publications. Source: adapted after Rempelos et al. (2020b)

Reference	Super-structure									Sub-structure		
	Rail	Fastenings	Baseplates	Fixings	Fishplates	Sleeper				Ballast	Geotextile separator	Sand blanket
						Concrete	Hardwood	Softwood	Steel			
Künniger and Richter (1998)	✗	✗	✗	✗	✗	?	24-30		?	✗	✗	✗
Ueda et al. (1999, 2003)	✗	✗	✗	✗	✗	50	15		50	✗	✗	✗
von Rozycki et al. (2003)	30	✗	✗	✗	✗	30	✗	✗	✗	15	✗	✗
Owens (1997)	✗	✗	✗	✗	✗	60	25-30	✗	✗	✗	✗	✗
Werner (2008)	✗	✗	✗	✗	✗	35	30		30	✗	✗	✗
Chester (2008)	25	✗	✗	✗	✗	50	25	✗	25	25	✗	✗
Kiani et al. (2008)	20-30	20-30	20-30	✗	✗	20-30	✗	✗	✗	20-30	✗	✗
Crawford (2009)	✗	✗	✗	✗	✗	30-50	20-30	✗	✗	✗	✗	✗
Network Rail (2009)	30	✗	✗	✗	✗	30	✗	✗	✗	15	✗	✗
RSSB (2010); Tuchschmid (2009)	30	40	✗	✗	✗	40	25		✗	35	✗	✗
Milford and Allwood (2010)	13-38[1]	24-45[1]	24-45[1]	24-45[1]	13-38[1]	24-45[1]	16-36[1]	10-36[1]	17-40[1]	10-52[1]	10-52[1]	10-52[1]
Schmied and Mottschall (2010)	30	✗	✗	✗	✗	35	30		✗	15	60	60
Stripple and Uppenberg (2010)	45								✗	45		
Manalo et al. (2010)	✗	✗	✗	✗	✗	60	20-30	20	50	✗	✗	✗
Baron et al. (2011)	30	50	50	✗	✗	50 (twin-block)	✗	✗	✗	25	✗	✗
Tuchschmid et al. (2011)	30	✗	✗	✗	✗	35	30		30 (iron)	25	✗	✗
Bolin and Smith (2013)	✗	✗	✗	✗	✗	40	35		✗	✗	✗	✗
Ferdous and Manalo (2014); Ferdous et al. (2015)	✗	✗	✗	✗	✗	50	20		50	✗	✗	✗
de Bortoli et al. (2020)	30	30	✗	✗	✗	60	✗	✗	✗	30	✗	✗
Landgraf and Horvath (2021)	?	?	?	?	?	36-50	35		✗	?	?	?

[1] Upper/lower bound dependent on annual traffic load expressed in Equivalent Million Gross Tonnes per Annum (EMGTPA).

TABLE 2.4: Railway track component EFs from selected publications.
Source: adapted after Rempelos et al. (2020b)

Reference	Units	Super-structure										Sub-structure
		Rail	Fastenings	Baseplates	Fixings	Fishplates	USP/Rail Pad	Sleeper				Ballast
								Concrete	Hardwood	Softwood	Steel	
Ueda et al. (1999, 2003)		✗	✗	✗	✗	✗	✗	0.285	0.198	✗	✗	✗
von Rozycki et al. (2003)		1.864	✗	✗	✗	✗	✗	0.172	✗	0.098	✗	0.017
Chester (2008)	g/yd^3	543	✗	✗	✗	✗	✗	644	0.171	✗	543	0.014
Kiani et al. (2008)	GJ/t	16.10-24.00	16.10-24.00	✗	✗	✗	65.00-74.00	0.02-0.10 (aggregate) 3.50-5.60 (cement) 12.60-24.00 (steel)	✗	✗	✗	0.02-0.10
Crawford (2009)	$kgCO_2e/kg$	✗	✗	✗	✗	✗	✗	0.225	3.27	✗	✗	✗
Network Rail (2009)		1.810	✗	✗	✗	✗	✗	1.096	✗	✗	✗	0.014
Tuchschmid (2009)	$m \times a$	13.03	✗	✗	✗	✗	✗	6.51	✗	✗	✗	0.96
RSSB (2010)	$kgCO_2e/kg$	1.755	1.515 (cast iron) 1.755 (steel) 2.653 (rubber)	✗	✗	✗	✗	0.135	0.081	0.148	2.092	0.004
Milford and Allwood (2010)	$kgCO_2/kg$	1.38-2.78	1.71	1.91	1.71-1.77	3.19	✗	0.277-0.283	0.47	0.45	1.77	0.005
Baron et al. (2011)		1.629	1.937	1.937	✗	✗	✗	318.72 $kgCO_2/m^3$ (concrete) 1.35 $kgCO_2/kg$ (steel)	✗	✗	✗	0.004
Krezo et al. (2016)	$kgCO_2e/kg$	2.78	2.78	✗	✗	✗	3.0	0.277	✗	✗	✗	0.005
Ortega et al. (2018a)	$kgCO_2/kg$	2.02	1.68	1.68	✗	✗	2.83	0.215	0.459		✗	0.035

2.6.5 Switches and Crossings

Switches and Crossings (S&Cs) are complex multi-component assets (fifteen components, and eight design variables). Historically, these sections have taken about 23% and 24% of the renewal and maintenance budgets against a 5% of representative track miles (Cornish, 2014). Considering this, there is an increasing interest to quantify and reduce their LCC and carbon footprint, although the latter appears to be relatively under-researched to date.

Kaewunruen et al. (2015) examined the carbon emissions from a single re-construction project (a turnout, a diamond, and a crossover) and compared that to a bulk turnout renewal (3 turnouts, 2 crossovers), to investigate whether the latter successfully reduces the overall CO_2 emissions from special track work projects. The authors conducted site investigations, cost review, and expert interviews surveying the construction scales, materials, machinery, and construction methods used. They found that the machinery emissions typically varied between 15 – 17% compared to the embodied emissions, with the variations between these being below 1% among the examined re-constructions. Finally, it was found that by carrying renewals in bulk, the relative emissions reduce on average compared to the ones renewed individually. Kaewunruen and Lian (2019) established and analysed a 6D Building Information Modelling (BIM) for lifecycle management of a railway turnout. The BIM (level 3) has integrated 6-dimensions of field data information based on Revit-2018 and Navisworks-2018 platforms. Based on their model, they found that the embodied carbon emissions from the construction materials is the main contributor to the total carbon footprint, with the manufacturing, planning, and logistics phase accounting for the largest share of the footprint (56.8%); whereas, the reconstruction phase appeared to be the most cost-intensive. Kaewunruen and Liao (2021) evaluated the life-cycle carbon emissions and energy consumption of a railway turnout having composite bearers (i.e. Fiber-reinforced Foamed Urethane (FFU)) and compared them with those of a concrete turnout. They found that over a 75-year lifespan the two bearer options emitted almost identical amounts of carbon, whereas the total energy consumption of the composite turnout was significantly higher. Finally, the authors stressed that although the maintenance phase has been accounted for in their study, the number of interventions considered wasn't comprehensive due to data limitations as well as the large variability of energy consumption from plant, which can be significant from project-to-project.

More recently, Landgraf et al. (2022) evaluated and compared the environmental performance (of manufacturing, construction and maintenance) of two concrete turnouts (with and without USP) by conducting a process-based LCA, reflecting the conditions in Austria. They found that GWP has the highest contribution to the calculated environmental costs, accounting for between 87 to 97%. Considering the contribution of each phase, manufacturing (47%) and maintenance (43%) were found to be responsible for the highest share within the selected impact categories. Whereas, the construction phase accounted on average for just about 10%. Finally, the authors discussed the following key areas, were there is potential for minimising the environmental impacts of turnouts: (i) steel production, (ii) circular economy, (iii) use of alternative fuels for transport and plant, as well as (iv) the enhancement of component service life through the use of different interventions (e.g. USP). It was highlighted that potential improvements in steel production can result to considerable improvements, as steel components in turnouts were found to account for about 66% of the examined environmental impacts.

2.6.6 Ballastless track

Ballastless track is often promoted (both from a financial and an environmental perspective) as a replacement to conventional ballasted for longer life expectancy and reduced maintenance requirements. However, the literature is at best mixed for its environmental performance.

An early study by Kiani et al. (2008) found ballastless track beds to be more carbon and energy efficient than ballasted systems over long timescales. However, the results of such studies depend crucially on the assumptions made regarding service life, maintenance and annual traffic. Network Rail (2009) were unable to identify information that would allow them to make a comparison of the maintenance emissions between these systems, but they noted that the main benefits of ballastless track might be expected to arise from its reduced maintenance requirements. However, the replacement of ballasted track with slab systems has been found to increase embedded emissions significantly because four to six times more concrete is required (Network Rail, 2009). More recently, Pons et al. (2020) conducted a LCA to evaluate lifecycle environmental impacts of three different track designs (ballasted track, cast-in sleeper - Rheda 2000 and embedded rail track - BBEST). Based on their results, ballasted track performed better, regardless of the damage category considered for service lives of between 50 to 60 years. This is consistent with an earlier study by the UK Department for Transport (DfT). However, if the cast-in sleeper Rheda 2000 system were to last long enough it could start performing better than the ballasted system because of lower maintenance requirements. In Carbon terms extending the study beyond the standard 60 year design life and assuming the ballastless systems did not require replacement, a break-even point between the ballasted and cast-in sleeper systems was found to be at approximately 75 years of operation. At 100 years, the cast-in sleeper Rheda 2000 system displayed marginally better performance by emitting 5% less CO_2. Regardless of the examined service life scenario, BBEST performed the worst across most of the environmental impact categories considered (Pons et al., 2020). Krezo et al. (2016) calculated the GHG emissions of construction and use (i.e. maintenance and renewal phases) of the same three systems. Through a parametric analysis, they concluded that irrespective of the lifespan considered (e.g. 30, 60, 100 to 120 years), the ballasted system outperformed both ballastless options.

These results are not surprising considering the large quantities of concrete and steel required for the manufacturing of the two ballastless systems. Nevertheless, there are still opportunities to be exploited by substituting conventional materials with less-carbon intensive ones. For example, as discussed earlier RSSB (2010) suggested that substituting blast furnace slag or fly ash for cement as the cementitious material in concrete, could lead to emissions reductions. However, if carried out on a large scale, availability of the substitute material would be an issue as it is estimated that annual global cement production is 4.1 Gt (Levi et al., 2020) and annual granulated blast furnace slag production is 250 Mt (Globalslag, 2018).

2.7 Life cycle assessment tools

Dedicated commercial software tools have been developed for LCA (Table 2.5), with SimaPro and GaBi Software being two of the most commonly known products.

TABLE 2.5: Selection of LCA software from selected publications (adapted after Olugbenga et al. (2019)).

Reference	Method	LCA Analysis Tools			
		SimaPro	GaBI	Others	Database
Ueda et al. (1999, 2003)	CF	✓			✓
von Rozycki et al. (2003)	Screening LCA			✓	✓
Facanha and Horvath (2006)	Hybrid^{4}			✓	✓
Chester (2008)	Hybrid^{4}	✓			✓
Kiani et al. (2008)	CF			✓	
Crawford (2009)	Hybrid (Path Exchange)	✓		✓	✓
Chester and Horvath (2009)	Hybrid^{4}			✓	✓
Tuchschmid (2009)	Process			✓	✓
Network Rail (2009)	CF	✓			✓
Schmied and Mottschall (2010)	Process^{4}			✓	✓
Chester et al. (2010)	Hybrid^{4}			✓	✓
Chester and Horvath (2010)	EIO	✓			✓
Stripple and Uppenberg (2010)	Process			✓	✓
Milford and Allwood (2010)	CF			✓	
Grossrieder (2011)	MFA	✓			✓
Asplan Viak AS (2011)	Process	✓			✓
Tuchschmid et al. (2011)	MFA, CF			✓	✓
Baron et al. (2011)	MFA, CF			✓	✓
Chang and Kendall (2011)	CF^{1}			✓	
Westin and Kågeson (2012)	CF			✓	
Chester and Horvath (2012)	Process, EIO^{2,3}			✓	✓
Chester et al. (2012)	Hybrid^{2,3}	✓			✓
Chester et al. (2013)	CF^{1}	✓		✓	✓
Morita et al. (2013)	CF			✓	
Bolin and Smith (2013)	Process				
Miyoshi and Givoni (2014)	CF			✓	
Yue et al. (2015)	Process	✓			✓
Banar and Özdemir (2015)	Process	✓			✓
Matute and Chester (2015)	CF^{1}	✓		✓	✓
Chester and Cano (2016)	Process^{2,3}	✓		✓	✓
Cueno (2016)	CF			✓	✓
Hanson et al. (2016)	CF			✓	✓
Krezo et al. (2016)	CF			✓	
Lederer et al. (2016)	CF			✓	
Bueno et al. (2017)	CF			✓	✓
Saxe et al. (2017)	CF			✓	
Jones et al. (2017)	Process^{1}	✓			✓
Shinde et al. (2018)	Process		✓	✓	✓
Li et al. (2018)	CF			✓	
Ortega et al. (2018a)	CF			✓	
de Bortoli et al. (2020)	Process			✓	✓
Landgraf and Horvath (2021)	CF			✓	
Landgraf et al. (2022)	Process		✓		✓

[1] Process-based analysis.

[2] Attributional LCA.

[3] Consequential LCA.

[4] Unclear or not reported.

SimaPro was used by Chester (2008) as the basis for estimating emissions factors for track maintenance, and also by Ueda et al. (2003) for comparing EFs from different sleeper types, whereas the InnoTrack project used D-LCC (Ekberg and Paulsson, 2010). Similarly, Culbard (2009) made use of AEA's carbon impact tool to carry out an LCA of railway track replacement. There are also a number of more specialised tools which are designed for LCA (or elements of LCA) in specific fields, such as the International Road Federation's Changer software for estimating GHG emissions from road construction or the Carbon Management System (CMS) developed in Scotland (Fox et al., 2011).

Bespoke spreadsheet tools have also been used for LCA with some success, such as the Excel tools developed by Milford and Allwood (2010) and von Rozycki et al. (2003) for their analysis of railway track. Such tools tend to make use of external databases of EFs, such as the Bath Inventory of Carbon and Energy (an earlier version of which was used by Milford and Allwood (2010)), which provides a database of embodied energy and carbon coefficients for an extremely wide range of materials (Hammond and Jones, 2011). Alternative databases consulted for other studies include the Swiss 'ecoinvent' database of LCI data (Frischknecht et al., 2005), used by Spielmann and Scholz (2005) and by Tuchschmid (2009), and the emissions database produced by the Oko-Institut (Institute for Applied Ecology), used by von Rozycki et al. (2003). However, the Bath database appears unique in that it is freely available for download in MS Excel format. While limitations on data availability can still be a problem for LCA (Guinée et al., 2002), the range and reliability of data suitable for use in LCA is continually increasing.

Finally, a more commercial and easy to use tool has been developed by the UK government, which can be accessed via a website. Through different emission conversion factors GHG emissions are obtained. These conversion factors are updated annually and help agents convert their activities, such as fuel consumption or car mileage, into the equivalent carbon emissions (DBEIS, 2018).

2.8 LCCA for rail infrastructure

Many studies have been undertaken of Life Cycle Cost Assessment (LCCA) for rail infrastructure, with perhaps the most exhaustive carried out as part of the EU Innotrack project (Ekberg and Paulsson, 2010), which aimed to develop a standardised procedure for carrying out such analysis among different target groups from the top management – responsible for strategic decisions – to the specialists – responsible for technical decisions (Ripke et al., 2009). More recently, the costs of introducing new technologies to the railway industry at the macro-scale have been modelled, looking at the interactions between different elements of the rail system and the process changes involved in the introduction of such technology (Lovell et al., 2011). Aside of traditional LCC, there is a large body of literature focussing on methods of optimised maintenance planning. For example, a Mixed Integer Linear Programming (MILP) optimization model has been developed that integrates three individual degradation models for the rails, sleepers, and ballast (Caetano and Teixeira, 2015). In this study, maintenance/replacement regimes were scheduled opportunistically in a condition-based manner for adjacent track segments to minimise LCC at the line level. A later study by the same authors extended the utility of the model to the network level (Caetano and Teixeira, 2016), with the additional capability of studying the effects on LCC from reusing track components on secondary routes. A cost model has also been proposed to identify cost effective maintenance limits for track geometry (Arasteh Khouy et al., 2016). This model accounts for the degradation rates of different track sections alongside costs for inspections, tamping, accident risks, and delay time penalties. It was found that at higher intervention limits, tamping is not cost effective due to capacity loss penalties from regulatory speed restrictions, energy consumption, and ride comfort. Another study by Zhao et al. (2007) developed an optimization model for sleeper maintenance planning, targeting the minimization of sleeper replacements after inspection, while adhering to a set of requirements related to reliability and operational safety. Later work by Zhao et al. (2009) proposed a MILP model to optimize the scheduling plans of replacing concurrently ballast, sleepers, and rails in order to maximize the resulting cost benefit of combining different intervention actions for a given track section. They employed a genetic algorithm-based approach in order to find the most optimal solution.

Burrow et al. (2009) proposed a probabilistic asset management tool based on transition matrices, which was capable of evaluating the effects of different maintenance/renewal actions on the condition of the railway network over time, while accounting also for budget constraints and track standards. Another study adopted stochastic Reliability, Availability, Maintenance and Safety (RAMS) approaches (see section 3.4.2) to model the failure process of rails so that their maintenance procedure can be performed effectively (Kumar et al., 2008). A methodology based on Monte Carlo Simulation (MCS) has been proposed (Patra et al., 2009), including the design of an experiment for identifying uncertainties related to the estimation of LCC attributed to the statistical characteristics of reliability and maintainability parameters within a developed track maintenance cost model. More recently, a Whole Life Cycle Costing (WLCC) approach has been proposed to evaluate a range of different investment strategies in railway track maintenance (Sasidharan et al., 2020). The applicability of the model was demonstrated through an illustrative case study of three different route types in the UK. A linear regression model calibrated on historical track geometry observations was used to model track degradation. To address the uncertainties within their costing and input parameters, the authors conducted a sensitivity analysis of variations in these factors using MCS. Sasidharan et al. (2022) extended their previous work by incorporating a probabilistic risk assessment approach based on a combination of MCS and Fuzzy reasoning within their earlier model in order to account for uncertainties related with safety data.

Mathematical modelling languages such as Petri Nets (PN) have been also used extensively for railway track asset management, targeting in particular the estimation of LCC.

Andrews (2013) has modelled the degradation, maintenance, and inspection of single one-eighth mile sections. The transition times of assets degrading to different states were modelled for homogeneous segments by adopting a two-parameter Weibull distribution, for different track (region, rail, and sleeper type, speed classes, cumulative tonnage per annum) and life phase/state features (number and sequence of interventions implemented). This family of distributions is regularly adopted for such models (failure/degradation) owing to their flexibility to represent many different distribution shapes (Andrews and Moss, 2002). Moreover, they can provide failure analysis and prediction with a reasonable level of accuracy (Billington and Allan, 2006), while also dealing with small data samples (Audley and Andrews, 2013). This is particularly the case for the modelling of mechanical components such as rails, where their defects have shown to evolve following a Weibull law (Zhao et al., 2006). Andrews (2013) adopted these distributions to model the transition times, with the action thresholds for interventions and intervals for inspection being set as the decision variables. This methodology allowed the distribution of times to degradation events (states defined by the Standard Deviation (SD) of a number of maintenance characteristics) for a given type of track and maintenance history to be attained by monitoring the condition of respective one-eighth mile sections.

Andrews et al. (2014) extended the previous work by applying a PN architecture to predict track deterioration behaviour considering the effect of different asset management strategies, through the variation of different parameters (i.e. intervention threshold, inspection, renewal, routine repair time). Their analysis revealed that the intervention intervals influence the degradation rate, which changes accordingly from phase-to-phase. Considering the renewal times, the authors found that their extension poses no meaningful impact on the time that the track resides on a state of good condition. They demonstrated that by including the costs of performing different maintenance actions, as well as the penalty costs (associated with potential line closures or speed restrictions), the LCC of each maintenance strategy could be estimated. Whilst the proposed model can successfully forecast a track segments condition over long timescales, it is unable to make predictions at a track line level. Thus, a potential refinement of the model by considering a series of one-eighth mile segments will be beneficial as it will allow the integration of the conflicting requirements of tamping machines, as well as the ability to perform opportunistic maintenance.

Prescott and Andrews (2012) developed a model based on a PN methodology that permitted the analysis of a region of the railway network. By the term region, the authors defined a part of a network containing a number of one-eighth mile segments. A later study by Prescott and Andrews (2013) constructed a PN model in a modular fashion that allowed a number of regions comprising a railway network to be assessed in terms of track degradation, inspection, and maintenance. The primary innovation of this study compared to its predecessors is the integration of a maintenance Decision Support System (DSS) module in the PN's architecture. The decision for grouping the maintenance actions was based on the following parameters: (i) states of track degradation, (ii) machine availability, and (iii) section locations. Concluding, the consideration of criteria such as the total maintenance costs and line availability for grouping major works as per opportunistic decision-making principles will enhance the model's flexibility.

Rama and Andrews (2016) developed a framework involving an infrastructure performance model embedded in a LCC model to perform a whole-life costing analysis. They structured their model through a PN (including three core sub-nets: for degradation, inspection, and maintenance), which was primarily based on their previous work (Rama and Andrews, 2015). For the proposed infrastructure-state model, they adopted a hierarchical modular architecture, allowing a multi-asset configuration of the infrastructure (with varying degrees of complexity/detail) within a hierarchical topology of the network (a six-level architecture) to be portrayed. Thus, enabling the model to be utilised on predicting the performance both at an asset level (single maintainable item), but also at a system-wide level (whole network). This approach permitted the interdependencies among different intervention activities (i.e. opportunistic, concurrent maintenance, etc.) to be accounted for, and their subsequent, effect on costs and performance to be evaluated.

Similarly, Zhang et al. (2017) proposed a PN-based rail maintenance model underpinned by a MCS, comprising of several individual sub-nets for representing: degradation and defect/failure, inspection, maintenance, lubrication, and rail grinding. The resulting PN architecture feeds into a wider LCC framework, allowing the systematic investigation of different performance parameters (i.e. the number of interventions, maintenance costs, and deterioration profile of rails over their lifecycle). The researchers demonstrated the ability of the model to simulate the degradation profile of rails and evaluate their LCC over 35 years through a case study.

2.9 Infrastructure asset management

To lower track-related costs, and limit component failures, scientific techniques such as mathematical optimisation have attracted increasing attention in the recent years. These approaches are often used to aid dynamically techniques supporting the long-term assessment of decisions for systems with varying degrees of granularity. Such models in the context of railway infrastructure modelling can be roughly divided into: (1) deterioration modules, and (2) recovery (or restoration) modules. The former is utilised to approximate and predict the actual ageing process in condition or in reliability. The latter aims to determine the optimal times of inspection, and maintenance (or replacement), based on different sets of maintenance management policies. More recently, real-time data-acquisition successes and advances in computational methods generated a growing interest in the development of models to efficiently support the asset management process. However, the multitude of available studies brought about this new paradigm have confirmed the complexity of modelling track deterioration:

- The distributed nature of the system (termed as section-to-section variability) - meaning the existence of several covariates, varying along the section lengths;
- Lack of a complete understanding of the multiple interactions present between different track components;
- The difficulty of modelling the effect of a maintenance intervention on track quality, commonly, assuming that the track returns to an 'as-good-as-new' condition per intervention cycle;
- The difficulty of expressing *bona fide* decision-making, which can vary from IM-to-IM depending on (i) their organizational structure, (ii) budget constraints, (iii) network constraints (track time, availability of maintenance resources, crew scheduling), (iv) organization cultures (attitudes, beliefs, and sentiments), (v) other technical and organizational factors (design standards, in-house or outsourcing maintenance contracts);
- Lack of a complete understanding of the innate correlations between vehicle dynamics and track quality - displaying varying relationships even on sites of 'identical' track quality;
- The difficulty of modelling jointly different failure modes (such as shock and degradation failures);

- The difficulty of considering jointly maintenance and renewal models for different track components, due to their different degradation patterns, therefore losing important benefits of integrated planning through compromised maintenance and renewal decisions.

There have been several reviews related to alternative techniques, targeting different facets of the modelling process: data collection (Weston et al., 2015), degradation prediction modelling (Falamarzi et al., 2019; de Melo et al., 2020; Rempelos et al., 2023), maintenance planning/scheduling (Budai-Balke, 2009; Ferreira and Murray, 1997; Lidén, 2015, 2016; Li, 2017; Turner et al., 2016), DSS frameworks (Guler, 2012; Turner et al., 2016), as well as reviews considering a mixture of the above (Higgins and Liu, 2018; Soleimanmeigouni et al., 2018).

The following sections provide some background to the asset management software used for maintenance cost modelling and scheduling optimisation for rail infrastructure in the UK by NR.

2.9.1 VTISM

The program being used to estimate maintenance scheduling in Track21 (T21, 2021) and T2F (T2F, 2021) is VTISM aimed at providing a tool for appraising the whole life system costs stemming from the vehicle-track interface (Mills et al., 2011). It was developed by incorporating five different models: VAMPIRE a vehicle dynamics simulation, Whole Life Rail Model (WLRM), Track - Strategic Planning Application (T-SPA), Wheel Profile Damage Model (WPDM) and Wheelset Strategic Planning Application (W-SPA). Track and traffic data are obtained from the main centralised databases of NR which contain exhaustive information on different routes. In addition, VTISM encompasses an engineering database that includes standard and maintenance works. Basically, VTISM uses all the databases and models to forecast future condition and performance of the track by determining the deterioration based on the existing condition of the track and traffic volumes. Compared to other programs such as InfraCaLCC or STAMP, VTISM is the only tool that incorporates an asset inventory to provide accurate, up to date and empirical data to calculate the LCC (MAINLINE, 2013). The result is deterministic and expressed as the Net Present Value (NPV) per mile, either aggregated over all traffic or per train type and mile.

2.9.2 VTISM formulation

VTISM predicts and models maintenance needs and the effects of different maintenance strategies on costs relating geometry deterioration and ballast maintenance (Equation 2.1).

$$G(t) = LTSF \times BCF \times exp(at^b) \tag{2.1}$$

Where: $G(t)$ is the vertical short wave centred 35m rolling average filter SD at time t (t can also be substituted by cumulative tonnage and the constants a and b adjusted accordingly). This can be determined from measurements using a track geometry recording vehicle. $Exp(at^b)$ is an empirical relationship for geometry at cumulative time (or tonnage) t based on the track and traffic characteristics – the parameters a and b may relate to average or typical train type, weight, speed, frequency, etc. LTSF is the Local Track Section Factor, essentially a lumped factor to account for local track variation from the idealised deterioration rate, as determined from historical matching. BCF is the Ballast Condition Factor, a nonlinear relationship based on the fraction of the ballast voids filled with fines at any one time. The relationship allows for the introduction of fines due to traffic, environment, and dust from wagons and tamping maintenance.

A disadvantage of both the LTSF and BCF is that they coarsely lump together a variety of mechanisms of track deterioration, making it difficult to isolate the effects of any one of these, although the LTSF has in particular been linked with track stiffness.

Equation 2.1 can be applied for planned usage and projected into the future for different maintenance scenarios. It was originally developed for T-SPA, which is a decision support tool for strategic asset management developed by SERCO for NR, and has been incorporated in VTISM. T-SPA starts by taking a complete list of the assets and their condition at a particular time. This is obtained from a number of existing NR databases of infrastructure condition and traffic levels. This data is then projected forward in time, to predict which track assets will need replacing when and what this will cost. This prediction is done taking into account their initial condition and traffic usage. A number of time steps are taken, each equivalent to one month. At each time step, T-SPA takes the initial asset register at the beginning of the time step and calculates how much deterioration will occur based on the existing condition and the traffic volumes. Models are used to relate the traffic levels to changes in vertical geometry and the predicted number of vertical defects in rails and hence the likelihood of a rail break. Also, damage resulting from RCF (Rolling Contact Fatigue) and rail wear are included. This is the ageing process for the assets. The trigger level for a maintenance intervention is determined based on the linespeed. A reduced time period between interventions (e.g. tamps) is achieved by applying a 'damage' step to the BCF.

2.10 Conclusions

This chapter has outlined current best practice in rail environmental and economic modelling, summarised previous developments in the field and identified several areas where improvements could be made.

It is clear that LCA is crucial if a full picture of the impact of any infrastructure project is to be obtained. Considering this, hybrid approaches appear to be more comprehensive for overcoming the limitations of the traditional process-based method. It is also clear that LCA in itself is not sufficient to assess the viability of a project. LCCA methods should therefore be used to complement LCA and (if possible) take full account of the economic impacts in the decision-making process. Potentially these approaches can also be used alongside or as part of some form of Multi-Criteria Analysis (MCA) to allow for social impacts to be considered.

A large number of railway LCAs have been carried out by both researchers and consultants. System and geographical boundaries, lifespans, data, selected environmental impact categories, FU metrics, and technical specifications of the track forms are some factors of variability in these studies. Other common issues relate to the methodological framework adopted, with most studies following a process-based approach or variants thereof, largely ignoring its limitations. Only a few of these studies use field data, which may be understandable in the case of *ex ante* appraisals but less so for *ex post* ones (evaluations). Evidence from the literature suggest that reporting under a process-based framework, generally results in lower bound assessments, as the underlying methodology is based on bottom-up approaches (Olugbenga et al., 2019). Meta-analysis demonstrated that the timing of conducting an LCA within the project development cycle (*ex ante* or *ex post*) has also a significant impact, with reported results being higher for proposed than for constructed projects (Olugbenga et al., 2019). It is worth highlighting here, that this is possibly an effect of data limitations (at the early stages of the development cycle) but also of the heavy reliance on top-down approaches for transport appraisals at the route level.

As a result of the above disparities, most case studies appear to be incomparable, having both highly variable results but also heterogeneity in outcomes. Particularly, for railway sleeper appraisal, there is a lack of consensus on which variant has the best performance. This review also revealed that recent work has disproportionately concentrated on modelling the impacts of plain track, meaning that more complex structural layouts (e.g. bridges, S&Cs) have been comparatively neglected.

As part of this review a number of issues associated particularly with maintenance and EoL modelling were also considered. EoL appears to be commonly overlooked and in some cases that is considered, the underlying calculation and reporting methods are not transparently reported, to allow for further comparisons to be made. Considering maintenance and renewal interventions, these are mostly addressed superficially, more often than not, assuming arbitrarily selected fixed values, which dictate intervention cycles. This fact results in further variations between study results and also restrict the applicability of such models to examine reliably prospective improvements to the system. Adding to that, most studies that include such processes, incorporate them to varying degrees and with different boundaries, resulting to inconsistently calculated impacts. This fact was also confirmed for track construction processes by Olugbenga et al. (2019).

All in all, these issues highlight the one-off nature of these models, which makes it virtually impossible to compare similar schemes in different locations, or different interventions in a single location.

In summary, this thesis intends to make a significant original contribution to knowledge by filling some of the research gaps identified by this literature review. First, a framework will be developed based on bottom-up principles, having a clearly identifiable methodology, system boundaries and functional unit metrics, which will allow for appraisals to be made at different granularity levels (component, asset, route level), depending on the case study scope and data availability. The main intention is to create a modelling framework that will be generalised, standardised and highly replicable, qualifying it as a comparison enabling tool for examining potential improvements to the railway track system. This is very important for both stakeholders and academic practitioners as it will: (i) Create new perspectives for targeting lifecycle enhancements; (ii) aid on short and long term policy decisions - technical infrastructure choices, maintenance strategies, etc.; (iii) aid analysis (at different scopes) due to its transferability in terms of location, granularity level, etc. Secondly, it is intended for it to be compatible with different degradation models, so as to transverse from purely static appraisals (based on engineering judgment - fixed values), moving towards science informed models, based on real world rates of deterioration. This is significant, because it will allow for reliable predictions to be made on the performance of different track modifications/interventions and assess the socio-economic case for altering current practice.

Finally, in terms of findings, the thesis aims at making an original contribution in three different areas. First, the proposed framework will be utilised at the **component level** to assess the performance of the most common sleeper types present in the UK network, and the findings will be compared against those of previous studies, in order to identify and better understand the reasons behind potential variations. Second, the framework will be extended at the **asset level** and investigate the whole life carbon footprint of a range of different S&Cs used in the UK. The novelty of this analysis lies on the fact that the modelling will be based exclusively on UK network-specific supply chains and production processes, and it will have considerable depth as it will focus on the entire lifecycle of these assets, but also breadth through examining a large number of both older and newer design variants. Third, the framework will be combined with an industry-specific asset management model and a method will be proposed to integrate the results of laboratory tests into the model, which will allow for newly introduced interventions to be examined. This will permit the assessment of a range of novel track system modifications from a whole life cost and carbon perspective (published research in this area is very limited) at the **route level**.

Chapter 3

Methodology: Developing an engineering economics approach

3.1 Introduction

This chapter starts by considering three groups of asset management methodologies that have the potential to be applied in railway infrastructure socio-economic modelling. The chapter continues with a detailed review of different methods for evaluating the whole-life economic and environmental impacts of railway infrastructure falling under the wider umbrella of project appraisal methodologies. Section 3.3 focuses on techniques for the appraisal of environmental impacts, providing a detailed review of Life Cycle Assessment (LCA), including its variants. Section 3.4 discusses Life Cycle Cost Assessment (LCCA) in the context of railway infrastructure appraisal, and then delves into potential extensions of this methodology for environmental accounting, discussing in detail the advantages, issues and limitations of such techniques, when compared with LCA. Section 3.5 focuses on a more widely known and commonly applied appraisal technique in the transport sector, known as Cost Benefit Analysis (CBA). Some alternatives to the traditional CBA are then presented in Sections 3.6 and 3.7, focusing on their advantages and subsequent applicability. Finally, the chapter concludes by explaining the reasons behind the choice of methodology and case studies for this thesis.

The objective of this chapter is to review the existing asset management methodologies that have the potential to be applied in railway infrastructure modelling and make a selection of the appropriate methods that can fulfill the objectives of this thesis. The expected outcome of this chapter is to identify an array of methodologies which will potentially form the backbone of the proposed modelling framework. It is anticipated that this framework will be formulated in an evolutionary manner in Chapters 4 to 6.

3.2 Appraisal and Cost Benefit Analysis

The increasing importance of sustainability for decision making over the past two decades, led to a growing stream of research and development of tools for project appraisal. Concerning civil engineering projects, the most widely applied tools, include, the Cost Benefit Analysis (CBA), Life Cycle Costing (LCC), and Life Cycle Assessment (LCA). Each of these tools is applicable under specific criteria for different forms of appraisal. This is further highlighted by the fact that given the considerable methodological disparities between them (Hoogmartens et al., 2014), conflicting results may be expected. Hoogmartens et al. (2014) reviewed each of these frameworks (Figure 3.1) and discussed the connections and coherence between them so as to exploit opportunities for adapting these to full sustainability assessment tools.

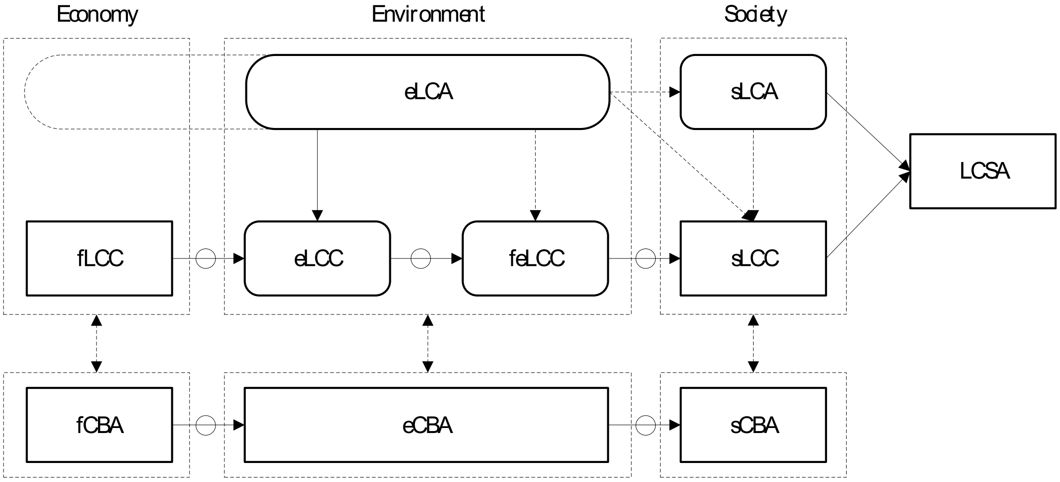

FIGURE 3.1: Illustration of interactions between different sustainability assessment tools (adapted after Hoogmartens et al. (2014)).
f : financial; e : environmental, s : social.

3.3 LCA

The procedures for a Life Cycle Assessment (LCA), also commonly referred to as a 'life cycle analysis' or 'cradle-to-grave' analysis, are set in accordance with the ISO (2006a,b), which form a part of the ISO 14000 series of environmental standards. ISO (2006a) defines the LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". This means that LCA is a tool assisting with the assessment of the different environmental facets and/or impacts throughout a products lifecycle, including all the associated phases ranging from raw material extraction until the final phase of recycling and/or final disposal.

The ISO (2006a,b) set down four phases that should be included in an LCA, these are illustrated in Figure 3.2.

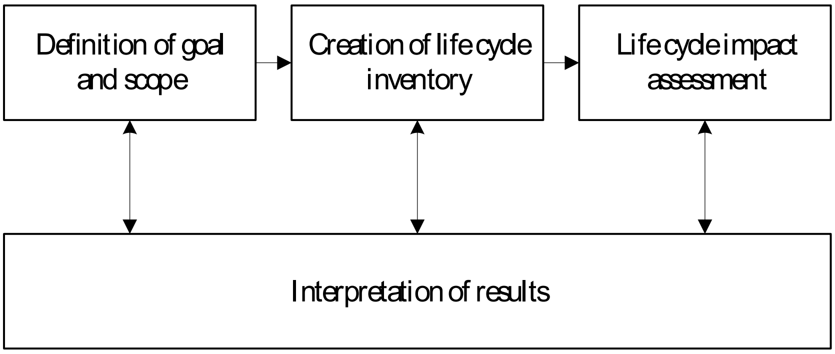

FIGURE 3.2: LCA phases.

A complete LCA considers a wide range of impacts and assesses their relative contributions to a diverse range of environmental concerns. Some of these impact categories are listed by Madu (2007), these usually range from resource depletion and direct/indirect greenhouse gas effect indicators to more sophisticated impact categories such as human toxicity, occupational health, eco-toxicity, noise, and even congestion, to name but a few. To define an LCA complete all the associated impact categories should be covered effectively and with transparency. Issues do however remain, as it is often the case that data is unavailable or even when data exists, it is often hard to quantify the extent of the environmental damage from the processes or products under investigation. Other issues that might hamper the outcome of an LCA include the lack of a standardised method of quantification and measurement of the associated damages to the environment (Madu, 2007). Madu (2007) lays down the principles of the LCA by highlighting that the aim of such an assessment is focusing on pollution prevention rather than its control.

The lack of methodological standardisation highlighted by Madu (2007) is a well-known issue to LCA practitioners. Considering this, Ahn et al. (2010) established a framework for estimating the carbon footprint of a tunnel. Whereas Kasozi and Tutesigensi (2007) proposed an indicator for environmental appraisal, conceptualised after the NPV, often employed at economic appraisals. This environmental indicator termed as Net Present Emission, allows comparisons between different projects in terms of their emissions. This is evaluated using a discount rate, but unlike economic appraisals, the meaning of discounting is to reflect the variable nature of emission sources and their sensitivity to variations in the type of fuel, energy efficiencies and levels of consumption. However, they stress the importance of developing a project-specific discount rate rather than utilising a standardised one, as the variable nature of carbon sources may hamper the realism of the studies' outcome. Its purpose will be to reflect the project-specific factors that exhibit variations (i.e. higher emission concentrations, technological innovations that offer emission reductions, incomes, material requirements, etc.).

3.3.1 Phases of LCA

3.3.1.1 Defining the Goal and Scope

The first and perhaps the most important phase of an LCA, involves the definition of the context of the appraisal and the clear and unambiguous definition of its scope and targeted audience. Broadly speaking the goal of an appraisal should state: (i) the intended application of the LCA, (ii) the rationale behind the practitioners' decision to conduct this study, (iii) the targeted addressees to whom the conclusions are intended to be communicated, and (iv) perhaps whether the analytical outputs are to be employed in comparative assertions and being publicly disclosed. ISO (2006a) clearly states that, "the scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal". The scope typically must include all the relevant items as described by the ISO (2006a) standard, meaning the System Boundary (SB) and the intended Functional Unit(s) (FU), the level of sophistication of the assessment relative to its pre-defined goal, the methods of allocation adopted to partition the impacts of shared processes as well as the impact categories selected. Finally, it is important to recognise any weaknesses imposed through assumptions and limitations. This effectively demonstrates the iterative nature of such an analysis, and that for the final goal to be met different aspect of the scope may require modification. It is often the case that following unforeseen imposition of limitations and data constraints, major revisions on the goal itself may be necessary.

Often it may seem, that by setting boundaries to the system, the results might be distorted and unrealistic. However, it is important to draw a line somewhere, as in certain cases the product chain might be traced *ad infinitum*, meaning that the quantification of the associated embedded emissions of the product may well be virtually impossible (Madu, 2007). Blainey et al. (2015) suggested as a good practice, to construct a fishbone diagram, as an assisting tool for defining the SB (see Figure 3.3).

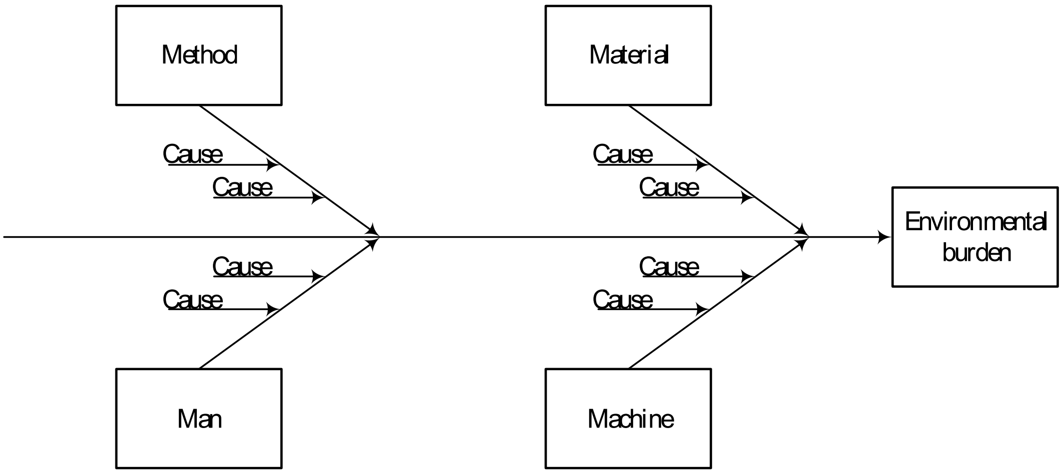

FIGURE 3.3: Cataloguing of emission causation using a Fishbone diagram.

Nevertheless, the imposition of SBs remains a 'soft area', ISO (2006a) suggests that in an ideal scenario the product system as a whole, should be modelled in a way that all inputs and outputs enclosed by the imposed boundary are elementary flows. However, it is often the case that when dealing with the quantification of embedded emissions, the definition of scope and SBs is proven not to be a clear-cut. Considering this, Pritchard and Preston (2016) described the case of certain tunnels being a part of the Channel Tunnel Rail Link, where Workman and Soga (2004), decided to exclude from their analysis the embodied energy originating from the factory that produced materials associated with tunnel lining. Pritchard and Preston (2016) argued that if the factory was built purposely for assisting this project, then its impacts should have been included on the analysis. This reinforces further the previous argument made, that albeit the importance of imposing SBs, a good understanding of these boundaries is the key for ensuring primarily clarity and confidence on the outcome of the study, and secondarily, consistency, which allow for future comparisons to be made between projects. The importance of SB in carbon footprint estimation has been also stressed by Matthews et al. (2008).

Thus, there is no 'silver bullet' to unravel every ill-defined SB issue. However, it is crucial to ensure that clear boundaries are being selected for any study to avoid ambiguity, when both specifying emission sources and at a posterior stage, interpreting results. Whilst, for unsophisticated models, devising project boundaries is less of an issue, for more multifaceted systems the selection process may be more challenging. This especially materialises, when the desired system to be modelled largely diverts from a product- or service-level or even a corporate entity or region of governance, by moving towards a multi-organisational industry-level, with its boundaries being less easily understood. In such cases, process diagrams like the one shown in Figure 3.4, can be employed to ensure a sufficient level of modelling 'resolution' in line with the goals of the study. Figure 3.4 is a reproduction of the process diagram used by RSSB (2010), on a pilot basis for the development of a more extensive and prescriptive methodological framework to determine the activities to be modelled on a carbon footprinting appraisal of the GB rail industry.

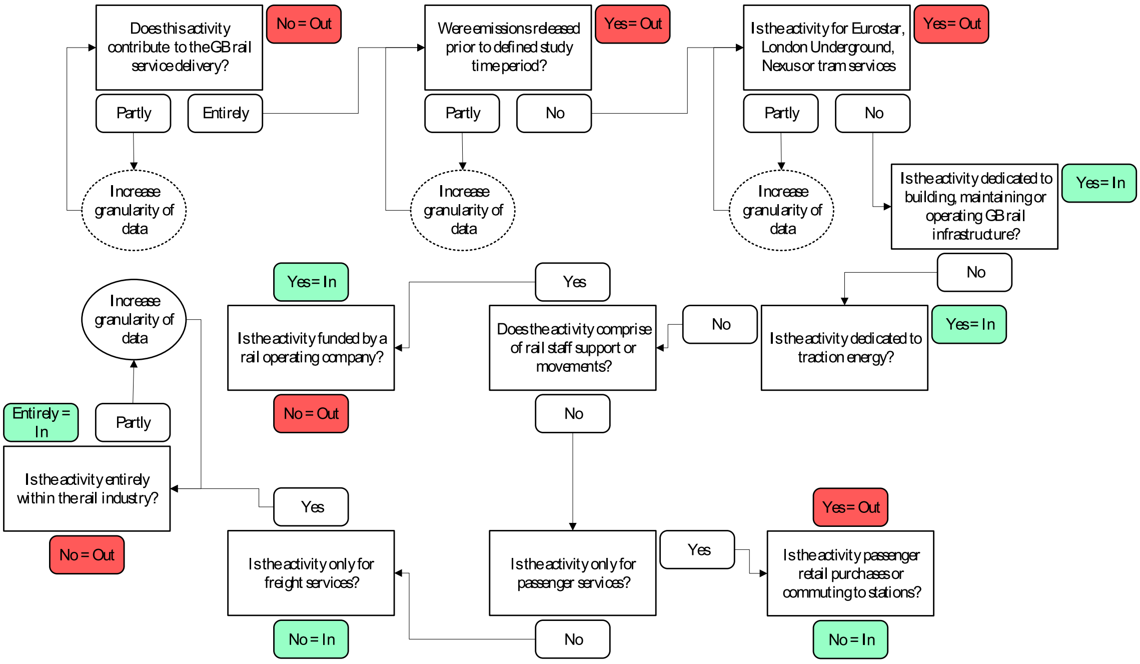

FIGURE 3.4: Process diagram for the selection of 'in-scope' activities on a carbon footprint study of the British railway industry (adapted after RSSB (2010)).

3.3.1.2 Creation of Life Cycle Inventory (LCI)

The second phase of the LCA is the Life Cycle Inventory (LCI) analysis. This is an inventory of all the associated input/output flows to and from nature and between different phases of the systems' lifecycle. This is achieved by creating a flow model, including all the relevant input/output data associated with the activities/products within the pre-defined SB. Often the definition of the elements of the system should be demonstrated via process trees, effectively cataloguing the associated activities included within the products' chain, these can be presented graphically in flow diagrams, with an example given in Figure 3.5. It is worth noting that a series of elements is missing (i.e. extraction, raw material processing, etc.) from the flow chart. Thereby, stressing the importance of carefully selecting correct SBs. While carrying out an LCA, all the associated flows must be traced until their economic inputs and outputs have been expressed into environmental interventions (Guinée et al., 2002).

To ensure consistency within the study, a standard data format is often introduced for the inventory, with the associated data categories being assigned to it (Guinée et al., 2002). The collection of data related to embedded emissions is usually sourced either through emission databases and/or bespoke studies. Following its completion, a table should be generated including all the associated input and output processes and FUs involved with the system under examination.

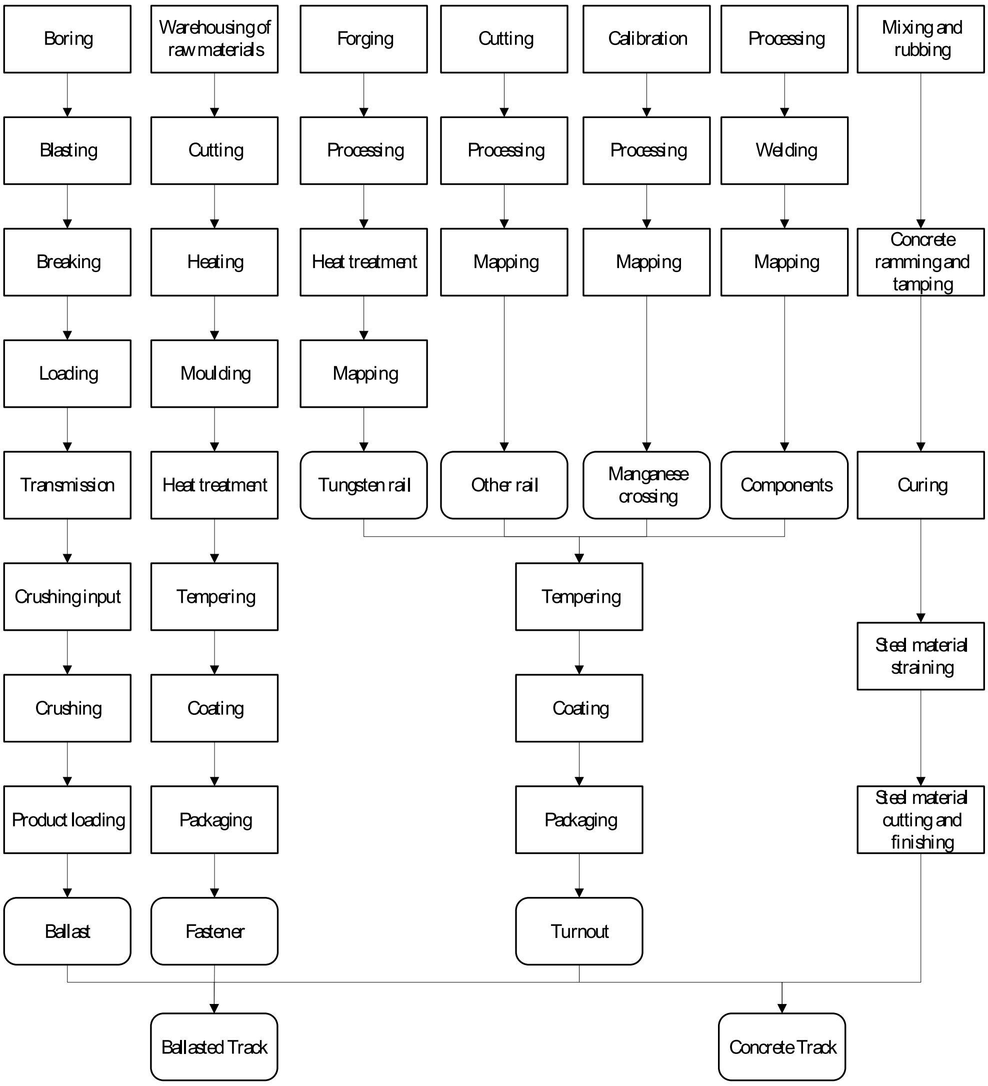

FIGURE 3.5: Process trees for the construction of ballasted and ballastless track (adapted after Lee et al. (2008)).

3.3.1.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) is the third phase of the LCA. The role of this phase is to effectively assist the assessment of a product system's LCI results, through additional information provision. This step allows for a more comprehensive understanding of the product system's environmental impact. ISO (2006a) defines this as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product". Essentially this phase involves the gathering of data from the inventory analysis and their classification and assignment with respect to the impact category they relate to, with the resulting emissions being estimated based on the LCI (Ueda et al., 2003). The subsequent evaluated impacts of each category are converted into a common unit and summed up, with a view to quantifying the overall impact for each examined category. These impacts can then be combined by first applying a weighting to them, and consequently, estimating the aggregate environmental load of the project. By considering all the associated stages of a product's lifecycle in the Life Cycle Impact Assessment (LCIA), issues such as problem shifting are by-passed (Guinée et al., 2002). Problem shifting is referred to as the transfer of an environmental issue through the product's chain to another stage in its lifecycle, this is often done to 'overcome' certain environmental issues. However, it is often the case that no overall improvement is being realised (Guinée et al., 2002). Certain issues still remain, if an individual process tree leads to the production of manifold by-products, making the assignment of emissions to products of interest virtually impossible (Madu, 2007).

3.3.1.4 Interpretation

The final phase of the LCA involves the summary, thorough discussion and evaluation of the results of the LCI/LCIA, or both, with a view to making conclusions and recommendations and discussing any associated strengths/limitations, in line with the goal and scope of the appraisal. ISO (2006a) defines this as the "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations". The element of 'evaluation' within this phase, is effectively a means of providing confidence in the results drawn from the LCA. The methods for a meticulous evaluation include sensitivity check, perturbation, completeness, consistency and uncertainty check, along with any other required validation, in line with the predefined goal and scope (ISO, 2006a).

A considerable number of limitations of the conventional LCA approach are deep-rooted within the phase of interpretation. Some of these limitations include the over-simplification of environmental problems to a monetary dimension, the lack of well-founded data, the high complexity of the construction process, and conceptual confusions (Gluch and Baumann, 2004).

3.3.2 Variants of LCA

Extensive literature exists on variants of LCA, and this section does not set out to provide a complete review, instead giving a brief summary of these variants.

3.3.2.1 Well-to-Wheel

This type of environmental appraisal is probably the most widely used form of assessment, at least when transport-related carbon emissions are concerned. It is performed to quantify the environmental impact associated with the productions, distribution and use of transport fuels, usually involving comparisons on a mode basis. However, it often shows a partial and perhaps misleading picture of a given mode's impact on the environment, with a classic example being rail in our case. When rail is concerned this type of studies often conclude that it is dominant over other transport modes, but they ignore the significant impact posed by its complementary infrastructure.

3.3.2.2 Gate-to-Gate

This is a form of partial LCA looking at an individual process within the product chain. While this form of analysis may be insightful when specific elements of the railway track system are concerned, it often leads to inconsistencies and it is prone to errors due to problem-shifting (Blainey et al., 2015).

3.3.2.3 Cradle-to-Gate

This is another form of partial LCA looking at the phases from the extraction of the resources until the point where the end-product is transported to the consumer. Consequently, the phases associated with the product use and disposal/recycling, etc. are omitted from the analysis. In other words, it focuses solely on particular stages of the lifecycle, and more often than not on the environmental impacts of a particular aspect (Bierer et al., 2014).

3.3.2.4 Cradle-to-Grave

This is the process described in section 3.3, It is also termed as 'full LCA' or 'process analysis'. It utilises a combination of process-, produce-, and location-specific data to quantify the impacts on the environment. Nevertheless, an issue of this assessment is that "it suffers from a systemic incompleteness, which is caused by the delineation of the assessed system by the finite boundary and the omission of contributions outside this boundary" (Crawford, 2009), meaning that the input system of the FU(s) may not be covered at a great extend from this type of analysis.

3.3.2.5 Cradle-to-Cradle

This is a form of full LCA for a product, where a type of recycling process is involved at its EoL disposal phase, and is also often termed as 'Open Loop Production'. Considering the rail track system, it is highly unlikely that this will apply to it as a whole. However, it may pertain to some elements, with an example being the rail steel. Nevertheless, some issues remain, as it is questionable where do the impacts originating from the original resource extraction should be accounted for in the system. In this regard, Fox et al. (2011) indicate the need to examine with care the implications of transport of recycled content specifications.

3.3.2.6 Life Cycle Energy Analysis (LCEA)

This approach considers all the direct (i.e. throughout manufacture) and indirect energy inputs (i.e. throughout production of materials, components and services) to a product, and also the energy inputs associated with the production of energy used during these processes (Cabeza et al., 2014; Ramesh et al., 2010). Furthermore, it accounts for potential energy recovery during the disposal phase of the examined products (i.e. through incineration, etc.) (Cabeza et al., 2014; Ramesh et al., 2010). Through this analysis the initial embodied energy in building construction can also be measured. This is related to the energy used in the material production (cradle to factory gate), transportation (factory to site gate) and construction (site gate to completion) phases, but not the energy recovered due to recycling.

3.3.2.7 Economic Input – Output Life Cycle Assessment (EIO – LCA)

This is an aggregate analysis, commonly utilised to determine the environmental impacts and the subsequent environmental performance by using financial data of different sectors of the economy to trace the resource requirements and associated pollutant emissions between these sectors (Crawford, 2009). This is more comprehensive when compared with process-based LCA, as effectively the whole economy is treated as a system, with all the associated direct and indirect requirements of inputs being modelled from other sectors, covering practically an *ad infinitum* amount of transactions upstream through the supply chain (Crawford, 2009). Nevertheless, while scoping issues often encountered when carrying out a conventional LCA for complex/lengthy production processes can be dealt with, the fact that it relies heavily on the sectoral agglomeration of establishments and commodities, may hamper the relevance of the outcome for any individual product under investigation (Crawford, 2009). Additionally, despite the fact that this technique uses the whole economic system as a boundary, which is the distinctive feature that gives great depth and breadth to this approach, it is also a leading contributor to its limitations (Crawford, 2009). This is because the reliability of results can be reduced, when financial flows are attributed to particular material quantities or emissions (Crawford, 2009).

3.3.3 Hybrid Life Cycle Analysis

There have been claims suggesting that due to the limitations of the EIO-LCA and the full LCA, the Hybrid approach combines their best elements. This is effectively a tiered procedure, where direct and downstream processes (manufacture, use and EoL) along with some imperative lower-order upstream requirements of the FU are appraised in detail under a full LCA framework (Crawford, 2009). The remaining higher-order upstream processes (extraction of materials, manufacturing) are examined through an EIO-LCA. Consequently, the SB selection targeting the production chain becomes obsolete, and the advantages of both modelling approaches, namely, specificity and completeness, are combined in the same framework (Crawford, 2009). Nonetheless, it is still the practitioner's responsibility to decide which processes are important and should be analysed under a full LCA framework. Consequently, the upstream truncation error for relevant items considered by the practitioner can be resolved (Crawford, 2009), but the potential of sideways and downstream truncation error remains due to the disaggregate nature of the supply chain, which does not allow the integration of process data (Crawford, 2009). Considering this, the modelling approach by Treloar (1997), termed as 'input-output-based hybrid analysis' can deal with these issues to some extent, by starting with a disaggregated input-output model to which the process data available is integrated into a full LCA. It is worth noting here that there exists a large variety of available hybrid methods in the literature, each one having its own advantages and limitations, for more details on the available methodologies the reader is directed to an excellent review by Crawford et al. (2018).

3.4 LCCA

3.4.1 Life cycle cost modelling

Short-term cost savings may not necessarily save money in the long run, and in order to be sure that a cost-minimising strategy is being pursued it is therefore necessary to undertake whole-life cost modelling, a form of project appraisal. This is undertaken using Life Cycle Cost Assessment (LCCA), sometimes also referred to as Life Cycle Costing (LCC) and Whole Life Cycle Costing (WLCC), which is a method for calculating the total cost of a system or product over its lifespan. There is sometimes confusion over the definition of these terms, and while they are often used interchangeably the latter two methods are not necessarily synonymous as, unlike some applications of LCC, WLCC (for which no international standard exists) is a dynamic approach which provides up to date cost and performance forecasts throughout the entire life of the infrastructure, in contrast with the static forecasts over a specified (and sometimes arbitrary) project life provided by LCC at the start of the project (Boussabaine and Kirkham, 2004). ISO 15686 defines LCC as being “a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs”. As is usual for appraisal procedures, all costs are discounted based on a single reference date, and the results of the LCCA will therefore be affected by the specified project length and discount rate (Ekberg and Paulsson, 2010).

LCCA models integrate six sequential stages in the life of a product or facility, which can be summarised as follows (Boussabaine and Kirkham, 2004):

1. **Justification for investment and client’s requirements.** This involves the development of a robust business case analysis, based on the reasons and requirements for investment in a particular product or facility, the perceived benefits, and the objectives which must be fulfilled to meet these requirements and generate the benefits (Boussabaine and Kirkham, 2004).
2. **Conceptual development.** This stage involves the translation of the project requirements and objectives into a conceptual plan for infrastructure which will fulfil them, and will thus require more specific costing data.
3. **Design.** Alternative means of implementing the conceptual plan are compared, with the best option selected based on strict criteria which take account of WLCC, benefits and risk levels.
4. **Construction.** This involves the selection of methods which will enable the preferred design to be built with maximum possible efficiency.
5. **Operation and maintenance.** This involves the determination of the most efficient and cost-effective means of operation of the infrastructure, while enabling it to meet the original project objectives. In the case of WLCC, this will be a dynamic process, as the optimal means of operation may change over time.
6. **End of economic life.** At this stage efforts are made to maximise the return from the facility at the end of its planned life.

In addition to this disaggregation of lifecycle stages, the product itself will also be disaggregated into a range of elements, which means that LCCA models effectively comprise a three-dimensional matrix. A significant element of the total costs will be fixed before the installation phase and, as this will often be the area where the greatest scope for savings exists, it is important that LCCA is undertaken alongside the earliest stages of project development (Ekberg and Paulsson, 2010). These costs may also be the easiest to estimate, as for example disposal costs will be much more uncertain than construction costs, requiring estimation of the residual value of the infrastructure at the end of the specified project life (Ekberg and Paulsson, 2010). There may also be uncertainty over how use of the infrastructure will vary over time, and it may be necessary to make allowances in the costing for potential system improvements to enable the infrastructure to continue to fulfil its intended role.

3.4.2 RAMS Criteria

In its most comprehensive form LCCA can enable a system approach by including, alongside the costs at all relevant phases, the technical behaviour of the product as described by the RAMS criteria (Reliability, Availability, Maintenance and Safety). The inclusion of these criteria means that in addition to financial cost, the analysis will consider the extent to which the system meets the objectives originally set out for the project and expected by its users (Ekberg and Paulsson, 2010). The key values included under the criteria will depend on the precise nature of the system and system requirements being analysed, but Table 3.1 gives some examples for railway track maintenance from the InnoTrack project.

Over the lifetime of the project (and associated analysis) the key input values should be continually reassessed and updated to ensure that they continue to give a realistic representation of the system (Ekberg and Paulsson, 2010).

The use of RAMS in railway infrastructure management is currently in its early stages, but Ekberg and Paulsson (2010) suggest that it should ideally be implemented across the rail infrastructure business. Commercial software such as ProRail can be used to carry out this type of analysis, although bespoke software may also be used in some situations.

TABLE 3.1: Key Values for RAMS Analysis of Railway Track Maintenance.
Source: Ripke et al. (2009)

Reliability	Availability	Maintainability	Safety
Mean Time Between Failure (MTBF) for corrective maintenance or failure rate (λ) or Mean Time To Failure (MTTF) or Mean Time To First Failure (MTFF or MTTFF)	Train delay hours	Mean Time To Repair (MTTR) or Mean Active Repair Time (MART) or Mean Maintenance Hours (MMH) or Mean Down Time (MDT) and Mean Logistic Delay Time (MLDT)	Hazard rate (e.g. rate of rail breakages)
Mean Time Between Maintenance (MTBM) for preventive maintenance	Passenger Performance Measure (PPM)	Repair Time or Mean Time Between Repair (MTBR)	Number of derailments due to asset
Mean Time Between Critical Failure (MTBCF)		Mean Time To Maintain (MTTM)	Number of accidents
Mean Time Between Service Affecting Failure (MTBSAF)		Mean Down Time (MDT)	

3.4.3 Analytic and Forecasting Methods

A range of analytic methods could be used as part of LCCA/RAMS analysis, including amongst others regression analysis of costs; time series cost analysis (with or without exponential smoothing); expert systems, fuzzy logic and Artificial Neural Network (ANN) analysis (Boussabaine and Kirkham, 2004); root cause analysis; Failure Mode and Effects Analysis (FMEA); Failure Mode, Effects and Criticality Analysis (FMECA); Fault Tree Analysis (FTA); Event Tree Analysis (ETA); Hazard and Operability study (HAZOP); Preliminary Hazard Analysis (PHA); Markov analysis; and the Delphi technique (Ekberg and Paulsson, 2010), and will often be supported by commercial assessment tools.

Costings and other input parameters will frequently be subject to a degree of risk (for which a probability distribution can be defined) and uncertainty (for which no probability distribution can be developed) (Boussabaine and Kirkham, 2004). In such cases it is therefore usual to conduct sensitivity analysis of variations in these factors using techniques such as MCS (Bull, 1992).

3.4.4 Cost Calculations and Decision Criteria

Boussabaine and Kirkham (2004) specify three ways in which whole-life cycle costs can be calculated, and these can be summarised as follows.

3.4.4.1 Deterministic

$$WLCC = C_p + \sum_{t=0}^{n} \frac{C_t}{(1+d)^t} \tag{3.1}$$

Where:

$WLCC$ = total $WLCC$ in present value; C_t = sum of relevant whole life costs, including initial capital costs in year 0 and future costs up to the end life of the asset, less any positive cash flows such as the residual value of the asset; n = number of years in asset service life; d = discount rate; C_p = initial capital costs.

This method assumes that the magnitude and timing of all costs can be established in advance with certainty.

3.4.4.2 Stochastic

In practice, it is unlikely that there will be sufficient certainty about costs to allow deterministic calculation, but if probability distributions can be defined for all relevant cost areas then a stochastic approach can be used. Because different cost areas may have different probability distributions it is necessary for the calculations to be disaggregated by cost area. If the cost centres are statistically independent then $f(PV)$ can be assumed to follow a normal distribution.

$$f(PV) = f(C_p) + \sum_{t=0}^{n} \frac{f(C_{ti})}{(1+f(d))^t} \tag{3.2}$$

Where:

$f(PV)$ = probability distribution function of total $WLCC$ in present value; $f(C_{ti})$ = probability distribution function of relevant whole life costs for cost area i; $f(d)$ = probability distribution function of discount rate; $f(C_p)$ = probability distribution function of initial capital costs.

3.4.4.3 Fuzzy

The uncertainty associated with the project cost values will not always fit the assumptions associated with probability theory, and in such situations the use of fuzzy numbers to calculate the present value of costs may give the best results. The following equation gives an example of the type of formula used for such calculations (Kahraman et al., 2002).

$$\widetilde{PV} = \left(\textstyle\sum_{t=0}^{n} \left(\frac{max\left(P_t^{l(y)},0\right)}{\prod_{t'=0}^{t}\left(1+r_{t'}^{r(y)}\right)} + \frac{min\left(P_t^{l(y)},0\right)}{\prod_{t'=0}^{t}\left(1+r_{t'}^{l(y)}\right)} \right), \textstyle\sum_{t=0}^{n} \left(\frac{max\left(P_t^{r(y)},0\right)}{\prod_{t'=0}^{t}\left(1+r_{t'}^{l(y)}\right)} + \frac{min\left(P_t^{r(y)},0\right)}{\prod_{t'=0}^{t}\left(1+r_{t'}^{r(y)}\right)} \right) \right) \tag{3.3}$$

Where:

$P_t^{l(y)}$ = left membership representation of whole life cycle cost at time t; $P_t^{r(y)}$ = right membership representation of whole life cycle cost at time t; $r_{t'}^{l(y)}$ = left membership representation of discount rate at time t; $r_{t'}^{r(y)}$ = right membership representation of discount rate at time t.

3.4.4.4 Decision Criteria

As in any form of appraisal, if more than one potential scheme or strategy is being compared, it is necessary to specify some form of criteria for deciding between them. A number of criteria were compared during the Innotrack project (Ekberg and Paulsson, 2010), with NPV found to be the most accurate procedure for decision support, particularly if complemented by an Annuity Factor (AF) (the regular constant payment per year), the break-even point (payback period) or the Internal Rate of Return (IRR) (Ekberg and Paulsson, 2010). Other measures which may be used include Simple Payback (SPB), Discounted Payback (DPB), Return On Capital Employed (ROCE), Net Savings (NS), Savings to Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR)[1], Net Terminal Value (NTV), sinking funds, Benefit Cost Ratio (BCR) and Total Annual Capital Charge (TACC) (Boussabaine and Kirkham, 2004).

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[1] Unlike IRR, it assumes that any savings from an investment can be reinvested back at the discount rate for the remaining life of the project (Boussabaine and Kirkham, 2004).

3.4.5 LCCA approach for environmental accounting

Traditional LCC is a type of investment calculus used to rank different investment alternatives (Gluch and Baumann, 2004). Its main difference (and advantage) compared to traditional investment calculus lies on its expanded boundaries taking a so-called lifecycle perspective by including recurring expenditure for operation alongside one-off investment costs. The origins of this method trace back to the normative neoclassical economic theory, which suggests that firms follow the ideal of profit maximization, doing so by always operating under full knowledge (Cyert and March, 1963). This implies access to 'perfect' information on the consequences of each of their preferences and alternatives, combining this with the expected utility, in turn weighting or discounting outcomes by their probability of occurrence (Gluch and Baumann, 2004). Under such notion *homo economicus* is seen as a rational being in a 'utopian' world where no information asymmetries are present. In consideration of the foregoing, according to Gluch and Baumann (2004) there are certain limitations deep-rooted on the neoclassical economic theory that restrict its use in an environmental context:

1. First, assuming that the decision-maker is always rational (behaviour of the economic man) and has access to perfect information on alternatives and outcomes (lack of information asymmetry) undermines decision-making under conditions of genuine uncertainty.
2. Second, the assumption of alternatives being always present comes into conflict with the ecosystems evolutionary cycle, as for example, the extinction of species is not regarded as an issue, as there will always be alternatives to replace them without causing any imbalances.
3. Third, it disregards items that lack ownership rights, such as for example the natural environment.
4. Fourth, assuming that everything can be expressed as a one-dimensional unit (money), oversimplifies problems of multi-dimensional nature.

Concerning (1), decision-making is usually made under conditions of uncertainty, particularly in an environmental context, (i) consequences of a decision will most likely surface long after a decision was made, (ii) not necessarily on the same location, (iii) having cumulative rather than one-off impacts on ecosystems, which are difficult to detect, (iv) coupling of uncertainties/risks from likely changes of the socio-ecological system in the future, meaning that today's 'small change' may well be the unanticipated problems of the future (Gluch and Baumann, 2004).

Assuming the presence of countless alternatives (2), investment decisions in railway infrastructure may span over several decades and lead to irreversible outcomes, particularly in such context there is a sequence of decisions involved, with earlier decisions affecting the ones to follow, this fact coupled with the irreversible nature of eco-systems suggests that irreversibility cannot be disregarded as per neoclassical economic theory.

Considering (3), in economic theory rights to exploit resources (property rights) refer to any form of good or resource (Pearce and Turner, 1990). In this view, the environment is a resource (and property) in itself, yet its property rights are ill-defined, in turn complicating the existence of a market. Market's position in neoclassical theory has a central role as the primary mechanism for allocating resources efficiently. According to Gluch and Baumann (2004) pollution and environmental damage results from market mechanisms dysfunctioning owing to ill-defined property rights of the natural environment (Coase theorem).

The last point (4) concerns the notion of 'pricing the priceless' to simplify reality, which may lead to significant inconsistencies. Another important point relates to the time value of money, which is usually handled through discounting [2]. Discounting may lead to the depreciation of future consequences from decisions based on rates devised from today's view/knowledge of the market/environment. Gluch and Baumann (2004) proposed as an alternative to use an environmental hurdle rate (Equation 3.4) by Gray and Bebbington (1993). This technique uses three different hurdle rates set depending on the contribution of different costs to the environment. For example, by setting the red rates to zero, costs falling under this category are effectively not discounted over time, resulting on their impact on the total result being greater. Thus, hurdle rates can be accepted as long as future damage is assumed as negative as todays.

$$LCC = \sum_{t=0}^{T} P_{n,g} \times (1+g)^{-1} + \sum_{t=0}^{T} P_{n,y} \times (1+y)^{-1} + \sum_{t=0}^{T} P_{n,r} \times (1+r)^{-1} \tag{3.4}$$

Where:

P is the annual cost at time t; g is a green hurdle rate; y is a yellow hurdle rate; r is a red hurdle rate.

Another option proposed by Gluch and Baumann (2004) is using a differential escalation rate (e) to indicate relative pricing changes for cost items that are expected to increase more than others over time (Kirk and Dell'Isola, 1995):

$$LCC = \sum_{t=0}^{T} \left[P_n \times \frac{(1-e)^t}{(1+i)^t} \right] \tag{3.5}$$

Where:

P is the annual cost at time t; i is the interest rate; e is the escalation rate.

Aside of the issues vis-à-vis theoretical foundation of LCC (e.g. unable to capture uncertainty, items with no well-defined property rights, irreversible decisions, and future costs), it has the advantage of (i) taking a lifecycle perspective, (ii) adopting a familiar unit (money), and (iii) limiting information flow by streamlining multi-attributed alternatives. Thus, it remains of use for environmental accounting, which is the reason for seeing so many developments over the past decades (see Table 3.2).

Considering LCC tools, conceptual confusions may arise as different tools exist with various combinations of similar/identical/different (i) names, (ii) conceptual basis, and (iii) calculation principles, with practitioners occasionally using interchangeably terms from different methods (Gluch and Baumann, 2004). In this sense, LCC (or LCCA) and LCA are

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[2] The discount rate depends on inflation, cost of capital, personal consumption preferences, investment opportunities (Kirk and Dell'Isola, 1995; Perkins, 1994; Pike and Dobbins, 1986).

TABLE 3.2: Corporate environmental accounting tools.
Source: Gluch and Baumann (2004).

Concept	Definition/Description	Cost categories
Full Cost Accounting (FCA)	Identifies and quantifies the full range of costs throughout the lifecycle of the product, product line, process, service or activity (Spitzer et al., 1993)	Identifies and quantifies (1) direct, (2) indirect and (3) intangible costs
Full Cost Environmental Accounting (FCEA)	Embodies the same concept as FCA but highlights the environmental elements (Spitzer and Elwood, 1995)	Varying
Total Cost Assessment (TCA) (I)	Long-term, comprehensive financial analysis of the full range of internal costs and savings of an investment (Spitzer et al., 1993; White and Becker, 1992)	(1) Internal costs and savings
Total Cost Accounting (TCA) (II)	Term used as a synonym for either the definition given to FCA or as a synonym for TCA (Spitzer et al., 1993)	(1) Conventional cost, (2) hidden costs, (3) liability costs, (4) less tangible costs
Life Cycle Accounting (LCA)	The assignment of analysis of product-specific costs within a life cycle framework (Keoleian and Menerey, 1993)	(1) Usual costs, (2) hidden costs, (3) liability costs, (4) less tangible costs
Life Cycle Cost Assessment (LCCA)	Systematic process for evaluating the life cycle cost of a product or service by identifying environmental consequences and assigning measures of monetary value to those consequences (Bennett and James, 1997; Warren and Weitz, 1994). LCCA is a term that highlights the costing aspect of Life Cycle Assessment (LCA) (Spitzer et al., 1993)	Add cost information to LCA
Life Cycle Costing (LCC) (I)	Summing up the total costs of a product, process, or activity discounted over its lifetime (Henn, 1993; Keoleian and Menerey, 1993; Spitzer and Elwood, 1995; Spitzer et al., 1993)	Varying
Life Cycle Costing (LCC) (II)	A technique which enables comparative cost assessments to be made over a specified period of time; taking into account all relevant economic factors both in terms of initial costs and future operational costs [ISO15686]	Varying
Full Cost Pricing (FCP)	Term used as a synonym for FCA or LCC (Spitzer et al., 1993)	See FCA and LCC
Whole Life Costing (WLC)	Synonym to TCA [I] or LCC (Sterner, 2002). More specifically defined by Clift and Bourke (1999) as "The systematic consideration of all relevant costs and revenues associated with the acquisition and ownership of an asset"	(1) Initial costs and (2) operational costs

commonly treated as synonyms. Although the former refers to economic costs and the latter to ecological impacts. Another important difference concerns the concept of lifecycle. In LCC, we refer to lifetime[3] (or time), which can either be economic, technical, physical, or utility life (Kirk and Dell'Isola, 1995), with the choice between them affecting the study's time perspective and the subsequent LCC calculation when discounted to a NPV. Whereas, in the second approach (LCA), lifecycle does not reflect lifetime, but a physical chain of material flows related to a product, from resource extraction to waste management (Gluch and

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[3] For LCC analysis, the economic life is commonly adopted since the calculations most often have a cost minimisation perspective (Kirk and Dell'Isola, 1995).

Baumann, 2004). Despite their differences, it is desirable to integrate them in a single decision making process (Gluch and Baumann, 2004). Bierer et al. (2014) suggested Material Flow Cost Accounting (MFCA) for linking both methods, i.e. the monetary appraisal of materials, energy and losses of both which are needed to get a product through a particular process. Moreover, instead of focusing on the return on investments, the decision making processes should combine the economic costs along with quantitative social costs, and therefore, reconcile the findings of both approaches (Yu-rong et al., 2009).

3.5 CBA

In a full Cost Benefit Analysis (CBA) the monetary values of all significant positive and negative effects (whoever they accrue to and as valued by those affected) are compared for each scheme proposal. However, this may well be proven impossible, as monetary values cannot be obtained for all effects (Boardman et al., 2018; Layard and Glaister, 1994; Pearce and Nash, 1981; Rogers and Duffy, 2012).

3.6 Cost and Revenue Analysis

Cost and revenue analysis is a strictly financially oriented form of appraisal, usually focused on a single actor in isolation (Cole, 2005). It computes the monetary effects of alternative options to calculate their NPV to this actor using equation 3.6.

$$NPV_F = \sum_{i=0}^{n} \frac{R_i - O_i - C_i}{(1+d)^i} \tag{3.6}$$

Where:

NPV_F is the financial net present value of the scheme; R_i is the revenue in year i; O_i is the operating costs in year i; C_i is the capital costs in year i; d is the interest rate; n is the project life.

3.7 Cost-Effectiveness Analysis

This is a form of partial CBA, which is mainly utilised where a meaningful financial evaluation of costs and benefits of goods (or services) is not possible. In particular, it is appropriate for pure public goods, which can benefit jointly a lot of people and where it is difficult to differentiate people from the benefits (Layard and Glaister, 1994). Whenever CBA is impossible (e.g. benefits cannot be valued), it is still of use to compare the costs of providing the same beneficial outcome (Layard and Glaister, 1994). This approach is increasingly adopted in public health and healthcare settings, where CBA is considered inappropriate (Petitti, 2009).

3.8 Choice of case studies

The modelling methodology proposed in this thesis will be built following a combination of bottom-up and top-down approaches. This will allow for the model to be tested at three different granularity levels: component, asset, and route. This decision was made primarily to allow for the methodological framework to be tested under different scenarios in terms of input data availability. At the highest level of detail, results will be produced at the finest granularity (e.g. component level). The first case study (component appraisal) will focus on comparing the most common sleeper types present in the UK railway network, in a plain track layout arrangement. At the second level of detail, the capabilities of the initial model will be expanded from plain track to accommodate the appraisal of more complex layouts and the case study will focus on comparing the most common S&C layouts (asset appraisal) present in the UK railway network. Then the final model will integrate some methodological aspects and input data from the two previous modelling frameworks and expand upon those, driving the modelling capabilities of the appraisal up to the route level. The third case study will examine the applicability of the modelling framework by analysing the implications from installing a number of novel interventions for ballasted track, in order to examine the extent to which these are an improvement over existing systems. This will also allow for comparing the financial and environmental implications from alternative infrastructural investment strategies.

3.8.1 Component Appraisal

The first case study focuses on plain track and more specifically on the appraisal and subsequent comparison of the whole-life cycle costs and environmental impact associated with the four most common sleeper types present in the UK railway network. This decision was made as it has been revealed from the literature that the choice of material for railway sleepers is particularly controversial as evidenced from the largely conflicting conclusions from previous studies (Table 2.2). Additionally, little evidence has been found on performance comparisons of their LCC. Therefore, this was seen as an important candidate case study for the component level appraisal. Concerning the data requirements for this case study, these are discussed in Chapter 4.

3.8.2 Asset Appraisal

The second case study attempts to divert from the traditional plain track to more complex layouts that have been under-researched in terms of both whole-life cycle costs and environmental performance. Some of the reasons for the lack of research in this area include the complexity of these layout, the considerable factors of variability between different S&Cs, which both result to large input data requirements.

There are c. 21,704 sets of S&Cs on the UK network (over 3 units per 5 km of mainline track), with over 200 variants in design due to parameters such as switch lengths and angle of diversion route (Cornish, 2014). In order to identify the most commonly used design variants,

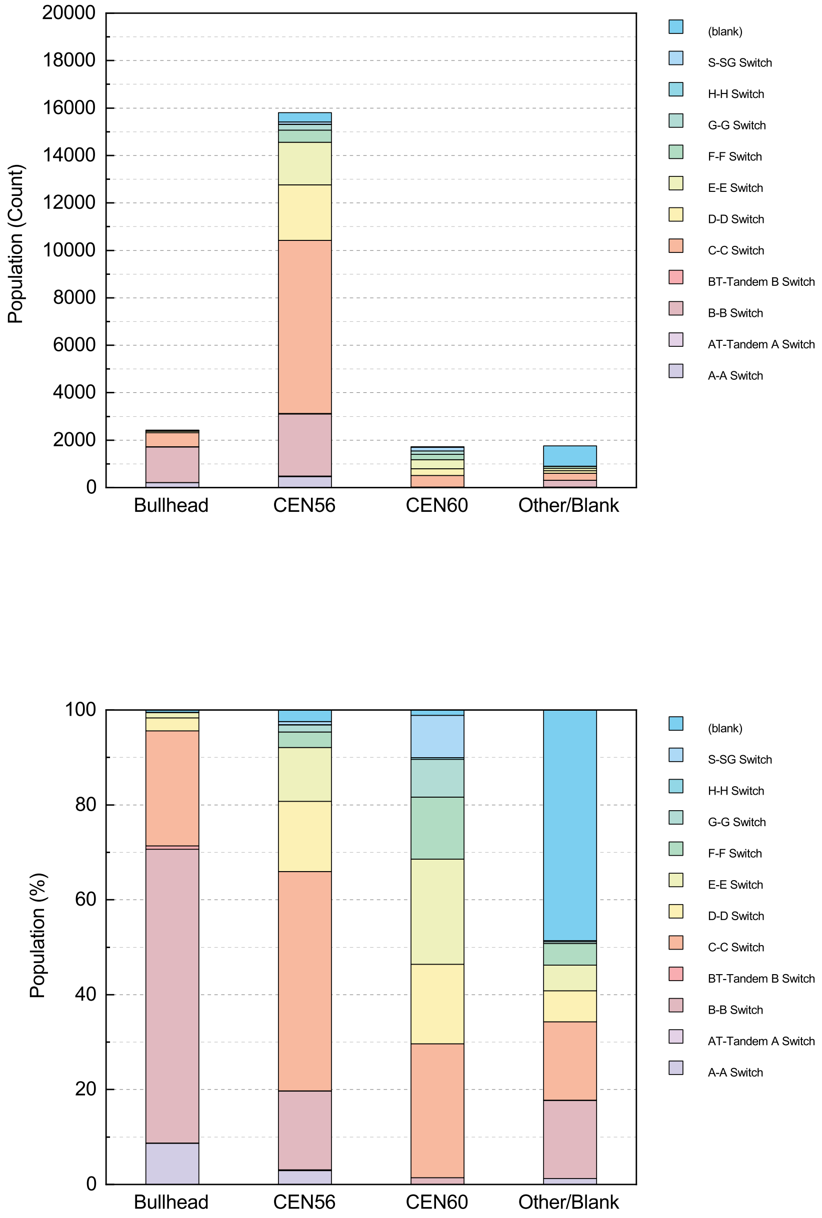

FIGURE 3.6: S&Cs population broken down by rail type and switch size.
Source: Crompton, M., 2021. Personal communication (Network Rail).

population data[4] have been requested from NR (Figure 3.6). These were broken down by rail type, switch size and crossing angle.

Following the initial processing of the data plotted in Figure 3.6, it has been decided to focus on the variants that use CEN56 (56 kg/m) and CEN60 (60 kg/m) rails. Moreover, the focus was placed only on turnouts (single unit) and crossovers (two units), which were further

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[4] Crompton, M., 2021. Personal communication (Network Rail)

shortlisted based on their switch size. It has been suggested by NR that there is no merit on breaking down these designs further, as the potential differences between them in terms of capital and carbon costs would be negligible. Considering other layouts, (e.g.) tandems, slips, etc. as these form a very small proportion of the total population, they have been excluded. Considering the above, data has been requested from NR and their supplier (Progress Rail) for 15 different designs (6 turnouts and 9 crossovers). The data requirements for the asset appraisal are discussed in detail in Chapter 5.

3.8.3 Route Appraisal

A limited access license was provided for VTISM, thus data was readily available for five specific routes (Table 3.3). Nevertheless, data could be request from Serco for the entire railway network of Great Britain, therefore there was no restriction on the choice of case study route.

TABLE 3.3: Candidate routes for route appraisal.

Route	**Location**	**Tonnage** EMGTPA	**Speed**	**Curvature** $< 2500m$ radius	**Type**
ECML	Main up line, from Edinburgh to Newcastle	Medium [16]	High	High [35%]	Interurban
GWML	Main downline from Paddington to Bristol	High [20]	High	Low [6%]	Interurban
MML	Main downline from Bedford to Derby	Medium [?]	High	Medium [25%]	Interurban
TPE	North Cross – Pennine Manchester	Medium [10]	Medium	High [35%]	Suburban/Commuter
SWML	South West Route, London Waterloo to Portsmouth	High [22]	Medium	Medium [25%]	Suburban/Commuter

There is also the possibility of simulating the performance of the entire network, although this would be very time consuming, and greatly limit the time for a meaningful appraisal of different interventions and scenarios. If an additional section (or route in a series of sections) is to be simulated, this should be defined through its ELR (Engineering Line Reference), TID (Track Identification), mileage (in mMiles) and route id. This information can be obtained from network hierarchy data held by NR. Data is also required on the vehicles and mix of traffic that is running on each section. These vehicle data files are already pre-registered in VTISM and no additional specification is necessary. This also applies for the traffic files that specify the number of vehicles that run over each section (based on NETRAFF). A limiting factor for the choice of route was that for simulating the WLRM and predicting the occurrence of RCF cracks and wear, and the loss of ground rail profile, new VAMPIRE files (obtained through Track-Ex) representative of the group of vehicles running on the route of interest are necessary. This fact restricted the candidate options into the five routes shown in Table 3.3, where complete data have been available. ECML and SWML were therefore chosen as the case study routes for appraisal. Aside from data availability, this selection was made on the basis of the different characteristics (e.g. speed, tonnage, curvature, etc.) of these routes, which can be particularly useful for examining the effects of, for example, speed and curvature on the carbon footprint and LCC. Further details on this case study and its data requirements are discussed in Chapter 6.

3.9 Choice of methodology

The literature review of previous work (Chapter 2) in the field of railway infrastructure appraisal revealed that no single methodology had been proposed which could fulfil the objectives of this thesis. Considering this, a mix of different methodologies (Figure 3.7) was adopted to appraise the economic and environmental performance of ballasted track. While it was shown that LCA and LCCA are commonly applied techniques for the appraisal of railway infrastructure, they are generally used in isolation. Therefore, there is a large scope for combining these methods to examine the trade-offs between cost and carbon for different Infrastructure Manager (IM) decisions.

An evident caveat of existing studies is the use of constant values to represent the service life of elements of the infrastructure. These practices result in traditional appraisal ignoring:

- the distributed nature of the system (section-to-section variability);
- the multiple interactions between different track components;
- the correlations between vehicle dynamics and track quality (displaying varying relationships even on sites of 'identical' track quality);
- difficulty of considering jointly maintenance and renewal models for different track components, due to their different degradation patterns, thereof losing important benefits of integrated planning through compromised maintenance and renewal decisions;
- the difficulty of expressing *bona fide* decision-making, which can vary from IM-to-IM depending on (i) their organisational structure, (ii) budget and network constraints (track time, availability of maintenance resources, crew scheduling), (iii) organisation cultures (attitudes, beliefs, and sentiments), (iv) other technical and organisational factors (design standards, in-house or outsourcing maintenance contracts).

Considering this, three different categories of models (mechanistic, empirical, hybrid) have been identified in the academic literature (Soleimanmeigouni et al., 2018; Rempelos et al., 2023). However, presently only a small number of these models have been loosely integrated in project appraisal (mainly for assessing financial LCC). Of these approaches, hybrid techniques appear to be more suitable for asset management, as they combine the advantages of both mechanistic and empirical approaches. In consideration of the above, this study will employ an existing industry – based hybrid-like tool and develop a generalised methodology for integrating laboratory data as inputs. Therefore, work in this study will focus on expanding the norm (pathway 2a vs. 2b in Figure 3.7) in railway infrastructure project appraisal and will allow for modifications to the existing systems to be examined, allowing estimation of the carbon footprint and LCC.

The methodology (Figure 3.7) can therefore be summarised as follows. The main framework for this study will adopt a life cycle perspective, involving the main steps of an LCA approach. However, the focus will be narrowed down to the assessment of the carbon footprint of the railway infrastructure. This will be complemented with an LCCA framework to assess different infrastructure strategies from a whole-life cost perspective. This is important as potential cost and carbon trade-offs between different infrastructure strategies can be identified. This core framework will be applied both at the component and asset level through two exemplar case studies. The framework will be then extended by introducing a procedure to modify the results of laboratory element tests as inputs to an existing hybrid asset management model to allow for newly introduced track interventions to be examined. These three methods will be then integrated into a single framework, implemented in Python, which will have the capability of forecasting the long-term performance of a number of novel track interventions at the route level and assess the case for altering current practice. Concluding, a MCS module will be also implemented in Python to assess the levels of uncertainty/certainty and contributing parameters to the analysis. It is intended for the module to (i) have the capability of simulating any number of variables (selected by the user) for a number of different distributions (defined by the user as well) for each parameter, and (ii) be transferable to any other problem/model programmed in Python.

3.10 Conclusions

This chapter starts with a detailed review of different project appraisal methodologies, which are discussed in the context of railway infrastructure asset management, highlighting also their strengths and weaknesses (Section 3.3 to 3.7). Section 3.9 explained the choice of methodology for this thesis and outlined its applications. These applications have been broken down in three different levels: (i) component, (ii) asset and (iii) route.

Chapter 4 will demonstrate the applicability of the proposed framework at the component level, by evaluating and comparing the performance of the most common sleeper types present in the UK railway network. Chapter 5 expands the capabilities of this framework, by incorporating a detailed LCI of different S&C design variants, enabling the quantification (at the asset level) of the whole life carbon footprint and carbon costs of fifteen (six turnouts and nine crossovers) different designs. Chapter 6 presents an extension of the framework, with the capability of examining the performance of novel modifications to the conventional ballasted track. A methodology based on relative settlement will be proposed to adapt the results of laboratory element tests into a suitable input into an existing industry – based track geometry degradation model, allowing the estimation of the carbon footprint and LCC at the route level. Finally, test results will be applied to two practical case studies, demonstrating the capabilities of the model in evaluating and comparing the long-term performance from the inclusion of seven novel track interventions, so as to assess the case for altering current practice.

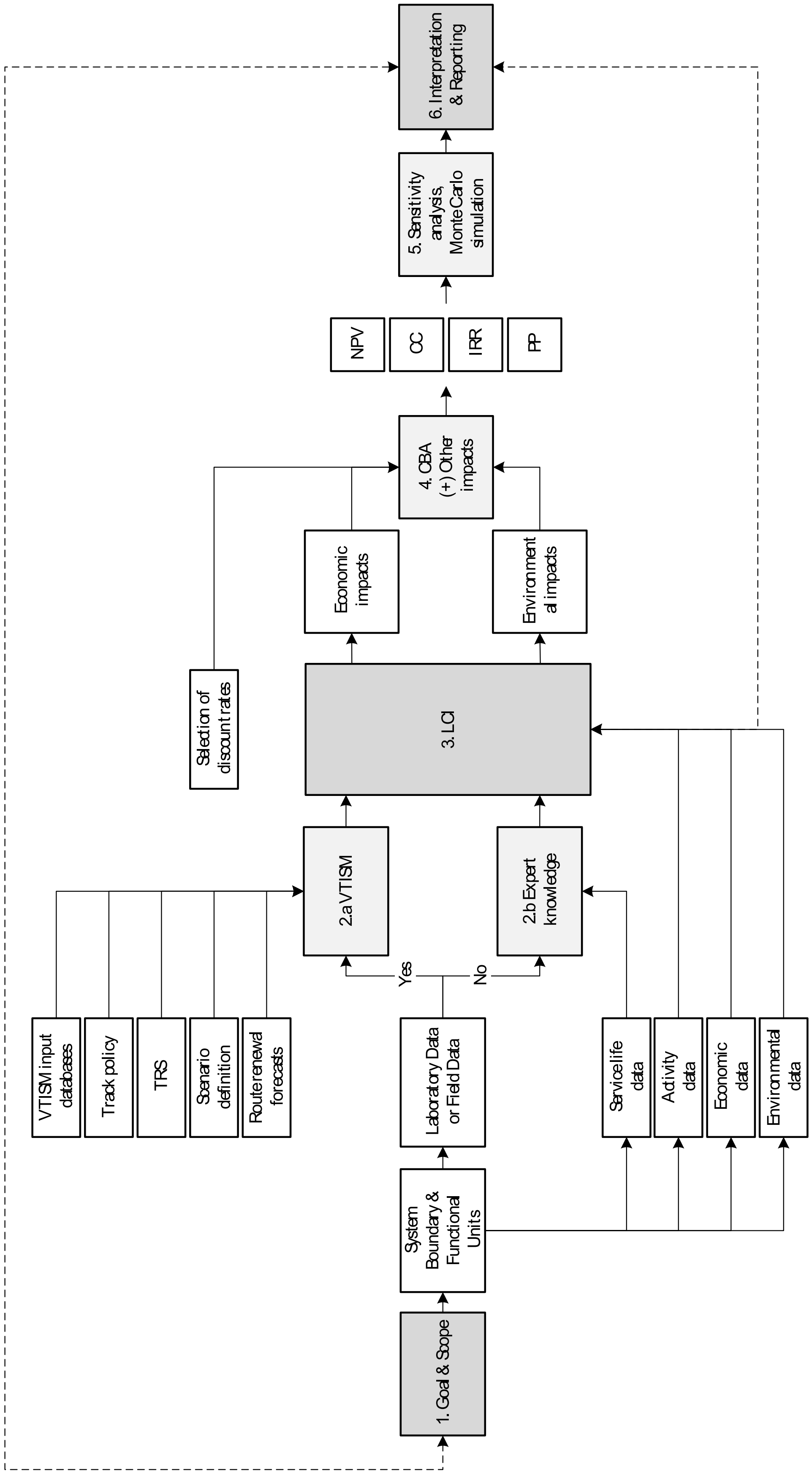


FIGURE 3.7: Overview of proposed modelling methodology

Chapter 4

Case Study I: Component appraisal

4.1 Introduction

LCAs (and structured carbon footprint analyses) are by their very nature rather time consuming and data/information intensive (Finnveden et al., 2009). This fact often stands in the way of their widespread adoption in the industry and policy-making sectors. Particularly for complex systems such as that of railway infrastructure, where decisions with potentially large environmental implications often have to be made under pressure from actors not in a position to wait for clear-cut and indisputable results. This translates to decisions being made by (often) neglecting their environmental dimensions. Most recent work on rail socio-economic modelling emphasises the need for a transferable albeit 'simple' methodology for the appraisal of different railway track forms. Tailor-made streamlined tools, with sufficiently reduced goal and scope and more relaxed data quality management standards can be useful in situations where less than perfect results are better than no results at all (Bala et al., 2010). This chapter therefore details the development of a modelling framework for environmental and financial appraisal of railway infrastructure by combining principles of streamlined LCA and LCCA approaches.

One area which has proven particularly controversial is the question of which sleeper material minimises whole-life CO_2 emissions, as wood tends to be viewed as being less carbon-intensive material than concrete. To date numerous studies (see Section 2.6.3) have explored this area, however, their findings are often conflicting (see Table 2.2). This is mainly a result of differences within their wider scope, such as the range of environmental impacts considered, the FUs and SBs used for the analysis, the LCA methodology used, the technical specifications of the track forms, and geographical and temporal variations in the datasets used for analysis. Against this background, the aim of this chapter is to bridge the knowledge gaps and address the limitations identified from previous studies in order to provide a more definitive study of the carbon footprint and financial costs of different sleepers types. This is done by an exemplar case study.

First, a modelling framework is developed for environmental and financial appraisal at the component level. Second, the applicability of the model is tested through an environmental and economic case study of the four most common sleeper types present in the UK railway network. Third, the results from this case study are compared against those of previous studies, examining the reasons behind potential variations, and quantifying the impact of different modelling choices on the results. While the conclusions from this chapter will be only directly applicable for the SBs of sleepers manufactured in the region of Great Britain, the modelling framework developed could be easily transferred to other geographic regions, and could therefore play a significant role in efforts to further reduce rail's environmental impacts around the world. Finally, although the application is UK-based, the analytical approach draws on international evidence.

4.2 Methodology

4.2.1 Scope

Given the above, this chapter critically appraises and compares the life cycle environmental impacts associated with the four most common sleeper types present in the UK railway network, namely, the G44 mono-block concrete, hardwood, softwood and the W560H steel sleepers. Broadly speaking, the most commonly quantifiable environmental impacts when it comes to the appraisal of railway sleepers are indicated by the GHG emissions and energy consumption. For this analysis, a spreadsheet model has been developed to evaluate the carbon footprint of different sleepers by adopting a streamlined life cycle approach and the results are presented using a CO_2e metric. This approach is in essence a slimmed down version of a complete LCA adopting all its core processes and excluding low contributing processes that would be otherwise included in a full LCA.

The subsequent evaluated emissions have been normalised over a km of single railway track ($t.CO_2e$ per km), to permit the summation of the environmental impacts of the different processes modelled within the examined products' life cycle. The key processes included in this analysis are broken down in the three core phases of the infrastructure's life: construction, relay/renewal and EoL, with the associated emissions being based on the devised table of EFs (see Table 4.1). The methodology adopted in this work is based partially on the framework described by Ashby (2009) and the conceptual LCA framework guidelines designated by the ISO (2006a,b) and BSI (2011).

4.2.2 Inventory Analysis and Functional Unit

The SB selected for the inventory analysis has been summarised in the Figure 4.1, the shaded processes represent the upstream and downstream stages which are not scoped in the appraisal. The methodological choices of this work are purposed for screening and preliminary evaluation (or initial 'hot-spotting') of these design alternatives, this is mainly a result of data limitations. Finally, it should be pointed out that the in scope activities, CFs, geographical coverage boundaries and track specifications adopted are chosen to represent the UK region.

As already discussed, the environmental indicator metric on this appraisal is CO_2 equivalent, with the associated emissions being normalised over a km of single railway track (stkm). The

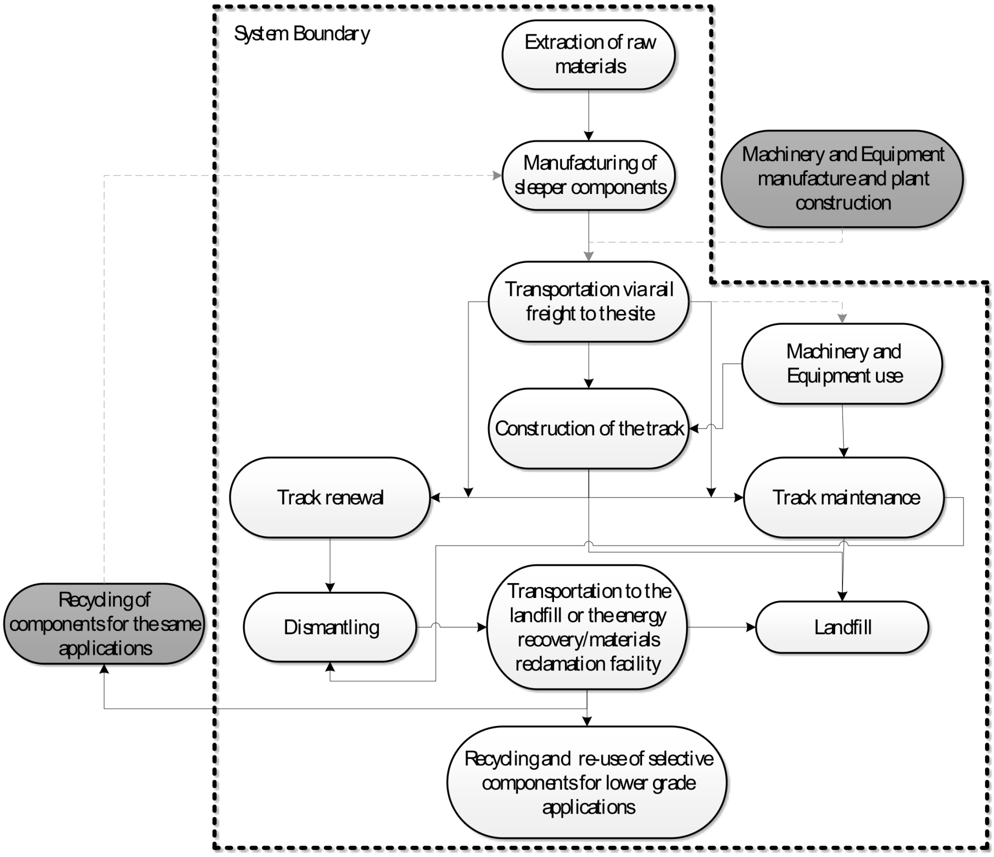


FIGURE 4.1: Simplified flow diagram and associated SB for the streamlined LCA carbon footprint model.

chosen FU includes only the railway sleeper component (either manufactured from concrete, steel, hardwood or softwood timber) excluding any auxiliary equipment such as fastenings, baseplates, fixings and so on. The primary reason behind the exclusion of these components is that in the UK routes there is a wide variety of baseplate and fastening combinations currently in use on various timber and concrete sleepers (approximately 17 types of fastening and 25 types of baseplates) (SUSTRAIL, 2012). According to SUSTRAIL (2012), a relatively small number of combinations of fastenings and baseplates are used in primary passenger routes in the UK as these are fairly standardised.

Considering the lifecycle adopted for this study, a 60-year appraisal period has been chosen in line with WebTAG recommendations (DfT, 2018), with the associated in scope processes being the raw material extraction, manufacturing of sleeper components, transport on site via rail freight, infrastructure use including the dismantling of obsolete components and the subsequent relay/renewal of new ones and finally, the EoL phase of the life-expired sleepers depending on the material present following the appropriate downstream pathway.

4.2.3 Model construction

4.2.3.1 Embodied Emissions

The Embodied Carbon Dioxide (EC) impact of the construction phase for each examined sleeper variant was estimated based on the material and carbon intensity values and the respective service life estimates based on the simulated load scenarios (see Table 4.1). The service life estimates in Table 4.1 are given in ranges to reflect the impact of different traffic loads on the sleeper renewal regimes.

The service life condition information are being drawn from the NR VTISM (SERCO, 2007, 2014) and is based on a mix of age and accumulated tonnage data recordings from UK routes. The material breakdown by mass is primarily based on the work done by Milford and Allwood (2010), with data drawn from their study being cross-correlated with other academic publications and manufacturer brochures, as well as data present within the RSSB's Rail Carbon Tool (RSSB, 2018). The embodied CO_2e emissions, EC_j^{c-g} 'cradle-to-gate' associated with the manufacturing of each sleeper variant were estimated by multiplying each material mass with the associated CF (Equation 4.1) quoted in RSSB's Rail Carbon Tool. These CFs are based on the Bath Inventory of Carbon and Energy (Hammond and Jones, 2011).

$$EC_j^{c-g} = LT/s \times \sum_{i=1}^{n} M_i \times C_i \times CF_i \tag{4.1}$$

Where: EC_j^{c-g} is the aggregate embodied 'cradle-to-gate' (c-g) CO_2e emissions for a track length LT laid with a type j sleeper in $kgCO_2e/FU$ selected; i is the material index; n is the total number of materials used in the construction of the railway sleeper; M_i is the mass of material i for each sleeper component given in kg; C_i is the % composition of each material to the total mass of the component; CF_i is the EC factor for each material i given in $kgCO_2e/kg$; LT is the chosen length of track given in metres; s is the UK sleeper spacing between centres given in metres.

In order to normalise the evaluated EC emissions per stkm, the standard sleeper spacing used in the UK railway network (600 to 700 mm between centres) has been used to calculate the number of sleepers per stkm (1,538 sleepers) and multiply them with the appropriate quantity of EC (in $kgCO_2e/sleeper$) calculated for each sleeper type.

TABLE 4.1: Basic infrastructural component characteristics.
Sources: Milford and Allwood (2010); RSSB (2018); SERCO (2007)

Sleeper	Type	Material	Composition by Mass	Mass	Embedded CF	Service Life
Component			%	*kg*	$kgCO_2e/kg$	years
Concrete	G44 Mono-block	1:2:4 Cement: Sand: Aggregate	95	309	0.124	24-45[1]
		Steel bar and rod - virgin (100:0)	5		2.77	
Hardwood	Western Australian Jarrah	Sawn Hardwood - General	100	70	0.87	16-36[1]
Softwood	French Maritime Pine	Sawn Softwood - General	100	60.2	0.59	10-36[1]
Steel	W560H	Steel with an avg. recycled content of 59%	100	74.5	1.46	17-40[1]
Steel	W400	Steel with an avg. recycled content of 59%	100	68.2		

[1] Upper/lower bound dependent on annual traffic load expressed in EMGTPA (10 low/60 high).

4.2.3.2 Component Processing

Additionally to the material manufacturing processes, components processing during track installation procedures including tasks such as rail cutting, welding, ballast spreading among others will also produce emissions. However, specific estimates of such figures are scarce, with the only set of information on component processing being the ones provided by Lee et al. (2008). Milford and Allwood (2010) posit that the emissions from the processing of track components typically contribute less than 8% of the aggregate footprint. In this study, the labour and plant emissions arising during construction have been estimated based on the machinery specifications of a Matisa TCM60 construction train with a sleeper laying productivity of 16 sleepers/minute and an engine size of 285kW (MATISA Matériel Industriel S.A., 2018a). Considering the labour and plant emissions arising during relay/renewal, these were estimated based on the machinery specifications of a P95 Matisa renewal/track-laying train (engine size 400kW), which is capable of installing concrete, steel and timber sleepers with an average working speed productivity of 1.1 km/hr (MATISA Matériel Industriel S.A., 2018b). The calculation of these emissions has been made indirectly using the equation 4.2 shown below.

$$EC^{s}_{L-P} = \sum_{i,j=1}^{n} LT/M_{P_i} \times PR_{ij}/100 \times PL_{ij}/100 \times CF_{ij} \tag{4.2}$$

Where, EC^{s}_{L-P} is the CO_2e emissions arising from the use of machinery and equipment for the construction, maintenance and relay/renewal on site in tonnes of CO_2e; i is the machinery index; $j = 1, 2, 3, \ldots, n$ corresponding to a rated power of $100kW, 300kW, 400kW, \ldots, n$; n is the total number of equipment used in the installation/renewal of the railway sleepers; LT is the length of track to be processed given in km; M_{P_i} is the track-laying train productivity given in $km/hour$; PR_{ij} is the % runtime of the engine j; PL_{ij} is the % load of the engine depending on the pre-defined engine size j; CF_{ij} is the CF for machine i with engine size j given in $kgCO_2e/hour$ of combustion (e.g. 237 $kgCO_2e/hour$ and 316 $kgCO_2e/hour$ for a 300kW and 400kW diesel engine respectively).

4.2.3.3 Component Transport Emissions

Emissions will also be produced from the transportation of components and materials associated with the construction, maintenance and/or renewal processes. Such emissions are highly ‘site-specific’, as they are dependent on the distance from the material source to the construction site, but also on the transport mode used. Milford and Allwood (2010) assumed an arbitrary selected transport distance of 200 km for all components, assumed to arise via rail freight. On this basis, they estimated emissions using DEFRA recommended EFs. Milford and Allwood (2010) highlighted that even with an arbitrary selected distance of this magnitude, transport from the factory gate to site typically accounts for less than 3% of the aggregate footprint. The CFs drawn from the RSSB’s Rail Carbon Tool are quoted as ‘cradle-to-gate’ rather than ‘cradle-to-site’ boundaries, and as this analysis does not consider any specific location, an arbitrary selected transport distance of 50 km has been chosen for all sleeper components, with the subsequent direct emissions assumed to arise via rail freight.

Consequently, in order to evaluate the direct embodied emissions arising from the transportation of the sleeper components, the Department for Business, Energy and Industrial Strategy (DBEIS) rail freight 'all scope' EF (DBEIS, 2018) quoted in $kgCO_2e/tonne \times km$ has been used (using equation 4.3).

$$EC_T = \sum_j \sum_i M_{ji} \times (T_{ji} \times CF_i)/1000 \tag{4.3}$$

Where, EC_T is the direct carbon emissions arising from the transportation of materials, equipment and waste expressed in tonnes of CO_2e; M_{ji} is the mass of building material, component, equipment or waste j (in *tonnes*) to be transported by vehicle i; T_{ji} is the total transport distance for item j transported via vehicle i (in km); CF_i is the EF to transport an item using vehicle i (in $kgCO_2e/tonne \times km$).

4.2.3.4 Carbon Emissions due to Temporary Works

Aside of the embodied emissions associated with the permanent building materials used on the railway infrastructure construction, maintenance and renewal operations, the rail industry consumes a sizable quantity of temporary materials to support different construction activities. This is particularly the case for the construction activities carried out for the installation of ballast-less track designs. For example, temporary materials such as propping elements and formworks are required to support the concrete slab during the curing process until it reaches the desired strength and being able to support its weight. These materials are often reusable for a certain time period up until they turn into waste and they need replacement. Consequently, the EC emissions originating from these materials follows a gradual depreciation over time and use. The exact same concept applies to the equipment used for supporting the construction, renewal, inspection and maintenance operations, where the initial embodied emissions of the equipment depreciates over time as it approaches its life-expiration time. Akbarnezhad et al. (2014) suggests that when the carbon footprint of construction is being evaluated, the depreciation of the EC of the equipment and temporary materials should be taken into account. Akbarnezhad and Xiao (2017) suggested the use of the following formulation in order to determine the amount of CO_2 emissions attributed to the gradual reduction in the remaining service life of the construction equipment and temporary materials:

$$C_C^{TM/E} = \sum_i (EC_i^{M/E} - EC_i^S) \times d_i^u / D_i^S \tag{4.4}$$

Where, $C_C^{TM/E}$ is the construction carbon emissions attributed to the depreciation in the EC of equipment or temporary materials (in tonnes CO_2e); $EC_i^{M/E}$is the EC of the temporary materials or equipment i as reported by the manufacturing company (in *tonnes* of CO_2e); EC_i^S is the salvage EC of the temporary materials or equipment i at the end of its serviceable life (in tonnes of CO_2e); d_i^u is the operating duration of the temporary materials or equipment i on the project given in hours, days or years; D_i^S is the service life of the temporary materials or equipment i given in hours, days or years.

Akbarnezhad and Xiao (2017) advised that the salvage EC of temporary materials or equipment *i* at the end of their serviceable life can be evaluated by investigating the final usability and/or fitness for use of the remaining components. They suggested that in case all the elements are to be recycled, the following expression should be used:

$$EC_{ij}^{S} = \sum_{j} (EC_{ij}^{R} - C_{ij}^{RP}) \tag{4.5}$$

Where, EC_{ij}^{S} is the EC of the recycled product obtained following the recycling of the component *j* of equipment or temporary material *i*; C_{ij}^{RP} is the CO_2 emissions arising from the processes involved on the recycling process of component *j* belonging to the equipment or temporary material *i*. Whilst there was the intention of including the embodied emissions from the manufacturing of the equipment used for the construction, maintenance and relay of the railway infrastructure, it has been decided for these emissions to be scoped-out of the analysis, as manufacturer quotes for this equipment could not be traced in the academic literature.

4.2.3.5 Track Maintenance and Renewal

Most studies considering railway infrastructure omit emissions resulting from track maintenance, and even in studies which do estimate the resulting emissions from such activities, there is often little detail of what is considered as forming part of such maintenance. Milford and Allwood (2010) estimated maintenance emissions from the three main maintenance activities carried out on the ballasted track (tamping, stoneblowing, rail grinding). The maintenance frequencies adopted in their study were based on estimates provided by NR, with the emissions being modelled indirectly based on the fuel consumption of the vehicles involved in these operations. Similarly, Chester (2008) estimated maintenance emissions (from material replacement, inspection(s), rail grinding) based on the equipment used and the labour productivity, as well as utilising rail maintenance EFs from the SimaPro software. More recently, Krezo et al. (2018) conducted a field-based study to evaluate the CO_2 emissions from the three main railway resurfacing activities (tamping, ballast regulator, and stabilizer). Based on their results, they found considerable differences (-55% to +26%) in fuel consumption and subsequent CO_2 emissions compared to earlier studies by Milford and Allwood (2010) and Kiani et al. (2008). They suggested that these arise due to differences in (i) costruction speeds (e.g. accounting for real-time delays) and also in (ii) diesel fuel EFs between Australia and the UK. Krezo et al. (2016) appraised that the CO_2 emissions from renewal/maintenance interventions are dominated by the EC (90-98%) of the materials used, with the remaining 2-10% being attributed to the machinery utilised.

In this study, the focus is placed on the appraisal of railway sleepers excluding any auxiliary equipment as well as other components such as rails and ballast that require frequent maintenance over their service life which will also produce a sizeable portion of emissions. Consequently, the only recurring emissions arising from the maintenance/renewal of the infrastructure were assumed to arise from the renewal of the sleeper components based on the service life threshold values shown in Table 4.1. Consequently, these life expectancy values define the amount of renewal operations required for each sleeper component. There is a large uncertainty surrounding these estimates as in reality the renewal of these components is heavily dependent on a wide range of factors. This means that in absence of recorded data the prediction of their service life is highly subjective and difficult to do with any certainty. As it can be inferred from Table 2.3, the service lives assumed for railway sleepers in different studies are highly variable with for example certain publications assuming a service life of as low as 20 years (Kiani et al., 2008) for concrete sleepers, while others suggesting a service life in excess of 50 years (Ueda et al., 1999, 2003; Chester, 2008; Crawford, 2009; SUSTRAIL, 2012). However, in the UK they are usually being replaced at the same time as rail at approximately 20 to 25 years, utilising the sleepers dismantled from the primary routes in secondary lines (SUSTRAIL, 2012). This suggests that an average of 31-52% of the sleepers on UK routes do not exceed 50% of their design life at renewal. This industry practice may contribute to additional financial, environmental and operational performance burden imposed to the responsible infrastructure authority.

In summary, the renewal emissions have been calculated using equation 4.6 shown below. The EC^{s}_{L-P} component of the equation which refers to the CO_2e emissions arising from the use of the machinery for the renewal of the infrastructure, includes the emissions from the sleeper dismantling, as these have been assigned to the renewal phase of the LCA instead of the EoL. This has been decided based on the capability of Matisa P95 track laying train to perform parallel dismantling and complete track bed renewal operation (MATISA Matériel Industriel S.A., 2018b).

$$EC^{s}_{R} = EC^{c-g}_{j} + EC_{T} + EC^{s}_{L-P} \tag{4.6}$$

Where, EC^{c-g}_{j} is the aggregate embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for a track length LT laid with a type j sleeper in tonnes of CO_2e per FU selected; EC_T is the direct carbon emissions arising from the transport of materials, waste and equipment expressed in tonnes of CO_2e; EC^{s}_{L-P} is the CO_2e emissions arising from the use of machinery and equipment for the construction, maintenance and relay/renewal on site in tonnes of CO_2e.

4.2.3.6 End-of-Life

A factor which is often overlooked in rail-related LCA studies, is the disposal of infrastructure when it becomes life-expired. Milford and Allwood (2010) posit that the emissions arising from the 'EoL' disposal phase of the infrastructure are predominantly related to transport. Nevertheless, the associated processes of dismantling, incineration and landfilling will also generate a sizeable portion of emissions. However, most of the existing rail-related studies largely omit the 'EoL' stage due to scarcity of process-specific information related to the exact pathway of infrastructural components. In this study, three EoL options for the sleeper components have been selected: (i) incineration, (ii) landfilling, (iii) recycling and subsequent re-use to lower grade applications. Considering the EoL characteristics for concrete sleepers, it has been assumed that 50% of the material is going to be recycled, while the remaining material is going to be landfilled. On the other hand, steel sleepers are assumed to be 100% recycled. The model excluded the emissions associated from the process of recycling as these lie outside the SB. These emissions would be included in the construction/manufacturing phase of a downstream recycled product. Consequently, the carbon dioxide equivalent factors adopted to represent the recycling process for concrete and steel only consider the transport to an energy recovery or materials reclamation facility. This approach is in line with the Greenhouse Gas Protocol (2004). The factors have been sourced from the latest greenhouse reporting database by DBEIS (2018) quoted in $kgCO_2e$ per tonne of concrete or steel landfilled or recycled respectively.

$$E(CH_4) = MCF \times DOC \times DOCF \times F \times 16/12 \times (1 - OX)^6 \tag{4.7}$$

Where, $E(CH_4)$ is the methane EF given in tonnes of CH_4 per tonne of waste wood landfilled; MCF is the methane correction factor which is recommended by IPCC (1996) to have a value of 1.0 for managed landfills; DOC is the degradable organic carbon which is recommended by IPCC (1996) to have a value of 30% for wood waste; $DOCF$ is the fraction of DOC dissimilated (i.e. converted to gas), recommended by IPCC (1996) to have a value of 0.5; F is the fraction of CH_4 in landfill gas – default value of 0.5 (IPCC, 1996); 16/12 is the conversion factor from carbon to methane (IPCC, 1996); OX is the oxidation rate which essentially accounts for the CH_4 that is oxidised in the uppermost layers of the waste mass and in cover material, where there is presence of oxygen - IPCC (1996) suggests a value of 0 as they note that there is currently no internationally accepted factor that can be applied to take into account the CH_4 oxidation – in this work a 10% oxidation rate was assumed based on the work done by Primary Power International (2004).

Following the estimation of the methane EF from the landfill of wood waste, 85% of these landfill gas emissions were assumed to be captured and burnt (substituting natural gas) as recommended by DEFRA (2006). This is proven to be a conservative estimate, as according to Milford and Allwood (2010) if the landfill gas was utilised as a substitute for grid electricity, the subsequent CO_2e emissions from the landfilling process of timber would be a net carbon sink. Finally, based on the aforementioned relationships, in order to derive the avoided CH_4 emissions from the landfill gas capture process equation 4.8 has been used.

$$E(CO_2e) = E(CH_4) \times W \times GWP \times C \tag{4.8}$$

Where, $E(CO_2e)$ is the avoided CO_2e emissions from the capture of the landfill gas given in tonnes of $CO_2e/tonne$ of wood; $E(CH_4)$ is the methane EF given in tonnes of CH_4 per tonne of waste wood landfilled; W is the quantity of wood to be landfilled given in tonnes; GWP is the global warming potential of CH_4 in CO_2e which is equal to 25 (Pachauri et al., 2014).

The second examined EoL pathway option for timber sleepers was incineration with energy recovery; however, due to the presence of carcinogenic coating attributed to the creosote impregnation process of timber sleepers, the base case scenarios excluded recycling or incineration as this practice is currently restricted in the European Union. Nevertheless, a ‘what-if-scenario’ has been tested on the worst timber sleeper scenario found in terms of environmental performance, in order to examine the extent of incineration required in order to offset the environmental dis-benefits of timber sleepers when compared with other sleeper alternatives. An issue with the evaluation of these emissions and also the subsequent benefits from the energy recovery during incineration was that the initial locked-up carbon resulted from the carbon sequestration during hardwood and softwood tree growth was unknown.

Moreover, it was unknown if this parameter was included in the embodied CFs quoted by RSSB (2018). In light of this, Milford and Allwood (2010) assumed no energy recovery from timber incineration to account for the carbon absorbed during tree growth. Nevertheless, in this analysis it is assumed that the energy recovery is feasible, with the subsequent calculation being made by assuming a heat content from the combustion of industrial wood of 3.306 kWh/kg of wood (Carbon Trust, 2016). The subsequent heat energy recovered was assumed to be once again used as a substitute for natural gas (0.183997 $kgCO_2e/kWh$) (Carbon Trust, 2016).

4.2.3.7 Non-energy Related Emissions

Locked-up Carbon

During tree growth, carbon is being absorbed from the atmosphere. This carbon is being maintained ‘locked-up’ in the timber’s structure and the subsequent structure of its downstream by-products up until the wood is either naturally decomposed or incinerated, resulting in the subsequent formation of CO_2 (Crawford, 2009). Crawford (2009) posits that this amount of carbon can be deducted from the carbon in the embodied GHG releases related with the fabrication of wooden sleepers. However, it was unknown if the locked-up carbon was included in the derived CFs for timber sourced from RSSB (2018). Therefore, it was decided to exclude this parameter from the model.

Roundwood Conversion Emissions

Aside of ‘locked-up’ carbon in wood, other non-energy related emissions include the emissions associated with the roundwood conversion of wood. “When forests are harvested, underbrush is disrupted, bark leaves and branches are stripped, and off-cuts and sawdust result” (Crawford, 2009). Crawford (2009) suggests that it is a common practice to either chip the roundwood conversion waste for use in wood products, or burn it either on-site or in kilns that are used for the process of drying timber or for other process heat, or alternatively leave it where it is. In his study, he assumed that the CO_2 originating from the roundwood conversion waste enters the atmosphere as GHG by assuming a factor of 40% as the share of biomass that is converted into hardwood sleepers, with the remaining 60% representing the timber waste to be treated as roundwood GHG emissions. However, as pointed out by Snowdon et al. (2000), this factor (roundwood conversion) can display a large variation ranging from 17 to 80% depending on the available market, type of forest and method of harvesting adopted. Aside from this, it can be argued that the locked-up carbon from the reclaimed waste for other products such as wood chips should be credited to them. Adding to this, if the purpose of forest harvesting is not only for the production of timber sleeper, which is usually the case, and the decision to harvest trees is linked with partially producing other products, then a subsequent portion of these aggregate emissions should be credited to them. These emissions have not been directly included in this study, however, there are indications suggesting that the embodied CFs adopted for timber include biomass process energy which is most likely originating from roundwood conversion.

Timber Decay Emissions

Following the timber harvesting process, carbon sequestration ceases and the process of timber decay onsets, with subsequent effect being the progressive release of the locked-up carbon back to the atmosphere. Crawford (2009) calculated the emissions from the eventual decay of new hardwood sleepers by assuming a carbon mass content for hardwood of 50%. Hence based on the derived CF for timber of 3.67 $kgCO_2/kg$ of carbon and a weight of 80.2 kg per timber sleeper, the eventual decay CO_2 emissions were estimated as 147 kg CO_2 per sleeper, with the complete decay assumed to be occurring after an 100-year period at a uniform rate over the sleepers' entire life (Crawford, 2009).

Carbonation of Concrete

It is well documented that concrete has the ability of chemically reacting with airborne CO_2 (see Salas et al. (2016)). However, the carbonation by concrete during its primary or secondary life is often omitted in LCA studies (Collins, 2010). Collins (2010) suggests that the carbon capture by built concrete during its primary life is more or less negligible. However, he stated that the CO_2 capture during the concrete's secondary life is significantly larger as the crushed product has a greater exposure to CO_2, as the larger surface area relative to volume results in higher levels of carbonation (Collins, 2010). This amount during the secondary life of the recycled concrete aggregate can be up to 41% of the carbon dioxide released during the production of 100% Portland cement binder (Collins, 2010). Collins (2010) posits that if carbonation is omitted, emissions figures can be overestimated by as much as 13% to 48%. However, he suggested that this range of overestimation will depend on the type of cement binder, as well as the destined application of the recycled downstream concrete product during its secondary life (Collins, 2010).

In this model only the CO_2 uptake during the concrete sleeper's primary life has been considered. This decision has been taken due to the fact that the recycling of concrete sleepers for the same application has been scoped out of the analysis as it is unknown if this is a common practice in the UK rail industry. Nevertheless, if waste concrete is being crushed in order to be used as a substitute for ballast material, it will contribute not only to avoiding the production of ballast from stone materials, but also it will reduce the amount of landfill waste, save resources and reduce the amount of CO_2 emitted from the production of virgin ballast (Stripple, 2013).

Aside of these benefits, crushed concrete materials can enable a rapid CO_2 uptake (in less than one year), while thicker concrete layers will carbonate in a slower pace (Stripple, 2013). Nonetheless, in order to realise the benefits from the CO_2 uptake of ballast made of recycled concrete, the waste material should be crushed and sieved accordingly, so its void ratio is considerable to enable air circulation (Stripple, 2013). The CO_2 uptake from the potential recycling of concrete for lower grade application such as for railway ballast was not included in the model, as the ballast component was omitted from the selected FU. However, it is worth pointing out that if the crushed concrete achieves the desired specifications to be used as a substitute for railway ballast, then the environmental profile of the concrete railway sleeper track is likely to be significantly improved.

Concrete sleepers are common products that are expected to carbonate during their service life. For the model calculations, the G44 mono-block sleeper has been considered with a weight of 309 kg per unit excluding fastenings, a length of 2.5 m, width of 0.285 m, depth of 0.2 m on the corners and a mid-span depth of 0.175 m. Using these dimensions the surface area distribution exposed to (topside, sides and ends = 1.8265 m^2) or sheltered from rain (bottom = 0.7125 m^2) has been estimated. The main surfaces have a good potential exposure to CO_2 even with 80% of the sleeper's surface being covered with railway ballast (Stripple, 2013). Hence, although the high quality dense concrete utilised for railway sleepers hinders the rate of CO_2 uptake of concrete during its use phase, the potential magnitude of uptake is high due to the high cement content in the concrete (Stripple, 2013). In summary, in order to calculate the annual CO_2 uptake for concrete sleepers, the derived estimates by Nilsson (2011) for exposed concrete structures to rain and sheltered structures from rain have been adopted and used to derive the relationships shown in Figure 4.2.

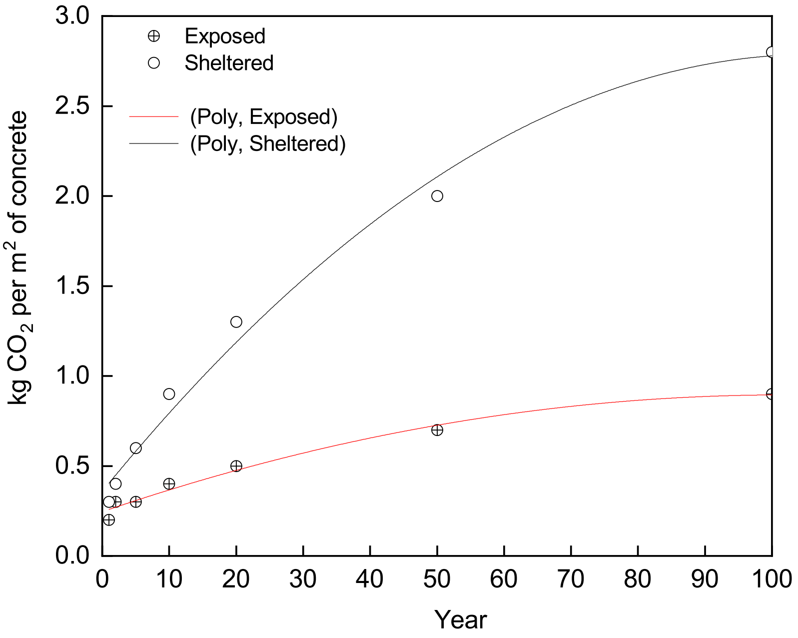


FIGURE 4.2: Derived relationships for the carbonation of concrete structures exposed to and sheltered from rain based on data estimates made by Nilsson (2011) (adapted after Rempelos et al. (2020b)).

These relationships have been used to estimate the carbonation (in $kgCO_2/m^2$ of concrete) of the exposed and sheltered portion of the concrete sleeper per annum which were multiplied by the exposed or sheltered area of the sleeper to determine the annual amount of carbonation (in $kgCO_2/sleeper$).

4.3 Results and Discussion

4.3.1 Simulated Scenarios

In total eleven programmed scenarios have been tested. These scenarios have been programmed using Visual Basic for Applications (VBA) excel spreadsheet models in order to enable variation in the modelling parameters with ease. The simulated scenarios differentiate in terms of: (i) track design (e.g. concrete, steel, hardwood, and softwood sleepers), (ii) traffic load conditions (either 10 or 60 EMGTPA), (iii) EoL pathway (e.g. assuming that timber sleepers are either 100% landfilled or partially landfilled and incinerated with energy recovery), (iv) installation of novel interventions (e.g. concrete sleepers fitted with stiff USPs). These scenarios are detailed in Table 4.2 below.

TABLE 4.2: Overview of simulated scenarios.
Source: Rempelos et al. (2020b)

No.	Label	Track Design	Load Condition	End-of-Life	Intervention
1	Scenario 1	Concrete sleeper	10 EMGTPA	$L\|R$[3]	no
2		Softwood sleeper		L[1]	
3		Hardwood sleeper		L[1]	
4		Steel sleeper		R[2]	
5	Scenario 2	Concrete sleeper	60 EMGTPA	$L\|R$[3]	no
6		Softwood sleeper		L[1]	
7		Hardwood sleeper		L[1]	
8		Steel sleeper		R[2]	
9	Scenario 3	Softwood sleeper Hardwood sleeper	60 EMGTPA	$L\|E$[4]	no
10	Scenario 4	Concrete sleeper	10 EMGTPA	$L\|R$[3]	USP (Stiff)
11		Concrete sleeper	60 EMGTPA	$L\|R$[3]	

[1] : Landfilling.
[2] : Recycling.
[3] : Partial landfilling and recycling.
[4] : Partial landfilling and incineration with energy recovery.

4.3.2 LCA Modelling Results

4.3.2.1 Carbon Footprint Results : Cradle-to-Site

The CO_2e emissions associated with the construction phase (cradle-to-site) of each sleeper type are common across all the simulated scenarios. These emissions are split in three primary areas: (i) EC emissions associated with the materials used, (ii) direct emissions associated with the transportation of materials from the factory gate to the construction site, and (iii) the emissions originating from the labour and plant (e.g. construction vehicles and machinery) during the track construction process. It has been found that the share of transport emissions to the aggregate footprint of construction ranges approximately between 0.1% and 0.8% (c. 0.19 to 1.0 $t.CO_2e/stkm$ in absolute terms) depending on the weight of the sleepers to be transported (as the mode of transport and the distance from the factory gate were capped across all scenarios and sleeper types). This translates to sleepers with higher unit weight (e.g. concrete) having a higher share of CO_2e emissions from transport compared to lighter alternatives (e.g. softwood timber). Similarly, the emissions originating from the construction equipment had a miniscule share of between 0.2% and 0.5% (c. 0.4 $t.CO_2e/stkm$ in absolute terms) of the construction footprint. The greatest share on the CO_2 footprint of construction has been found to be due to the EC associated with the production of materials, ranging between 54.6 and 167.3 $t.CO_2e/stkm$ depending on the type of sleeper considered.

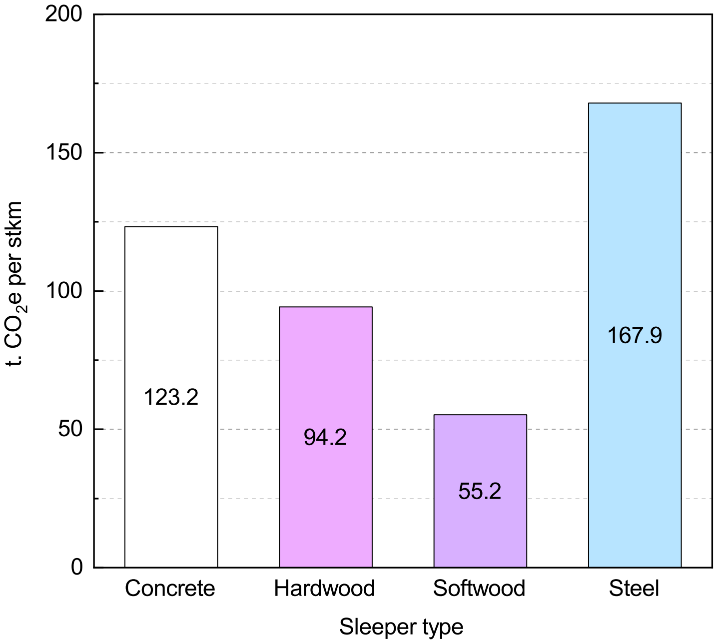


FIGURE 4.3: CO_2 impact from the construction (materials, labour and plant, transport) of a $stkm$ for each sleeper type (in tonnes of CO_2e emissions per $stkm$) (adapted after Rempelos et al. (2020b)).

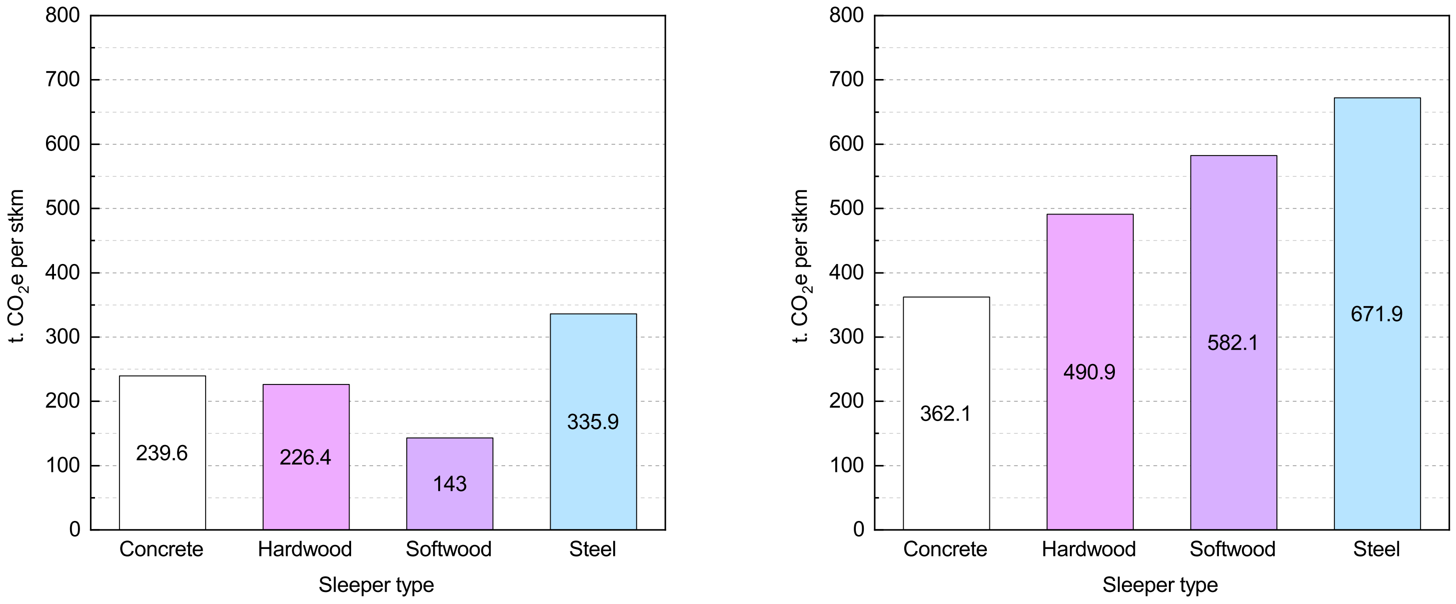
From Figure 4.3 it can be inferred that the steel sleepers have the greatest environmental impact during construction, which is approximately 36.6% greater than the next sleeper alternative (e.g. concrete sleepers). This should not come as a surprise, considering the sizeable mass of steel required and the highly carbon intensive process of manufacturing this component. At the other end of the environmental spectrum, the softwood sleepers made of French Maritime Pine, have three times smaller carbon footprint during construction compared to that of steel sleepers. Comparing the sleepers made of hardwood and the ones made of softwood, the former type has 60% more EC compared to the latter. The difference between the two can be explained partly due to their 9.8 kg mass difference and the 47.5% greater carbon intensity of the hardwood sleeper as expressed by its embedded CF.

4.3.2.2 Carbon Footprint Results : Cradle-to-Grave

Scenario 1 : 10 EMGTPA

The first simulated scenario assumed a low traffic tonnage of 10 EMGTPA. This scenario is broadly reflecting the tonnage of an inter-urban primary route. Under this scenario the softwood sleepers performed the best out of all the alternatives over a 60-year period. Hardwood sleepers displayed the second best environmental profile, however, they emitted 36.8% more CO_2e emissions compared to the softwood sleepers. The concrete sleepers exhibited marginally worse performance by emitting 5.5% more carbon compared to the hardwood sleepers. Notably, steel sleepers displayed by far the worst footprint by emitting 29% to 57% more CO_2e emissions compared to the other variants. The aggregate carbon footprint of each tested sleeper alternative is being displayed in Figure 4.4.

Looking at the breakdown of the overall carbon footprint by LCA phase (see Figure 4.5), it can be inferred that at low traffic loads the impact of construction is the greatest, accounting for between 38.9% and 51.4% of the overall footprint followed by the impact of track renewal which is marginally lower, as all the variants undergo only one major renewal during the whole simulated period. The impact of EoL phase for both the concrete and the steel sleepers is negligible ranging from 0.03 to 0.23% of the overall footprint. This is a direct implication from the modelling choice of recycling 100% of the steel sleepers and 50% of the material from the concrete sleepers. Conversely, the impact of landfilling of the timber sleepers' results in a sizeable percentage of emissions due to the releases of methane. This figure is ranging between 16.79% and 22.86% of the overall footprint for the hardwood and softwood sleepers respectively. As was expected, the impact of carbonation of concrete during its primary life is miniscule, accounting for approximately 3% of the concrete's aggregate footprint. Nevertheless, the carbonation of the recycled concrete product during its secondary life is expected to be significant, however, this calculation has not been incorporated into the model.



(A) 10 EMGTPA

(B) 60 EMGTPA

FIGURE 4.4: Aggregate carbon footprint of each sleeper design for a 60-year appraisal period for a low and high traffic tonnage scenario (adapted after Rempelos et al. (2020b)).

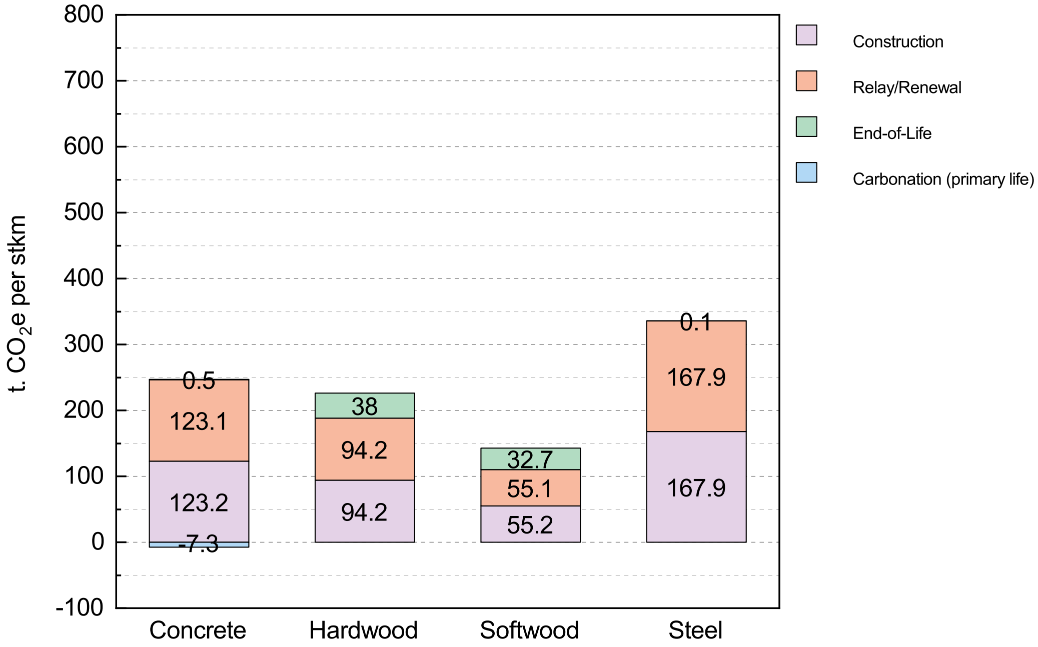


FIGURE 4.5: Carbon footprint for each sleeper type broken down by LCA phase for a 60-year appraisal period (10 EMGTPA) (adapted after Rempelos et al. (2020b)).

Scenario 2 : 60 EMGTPA

The second simulated scenario assumed a high traffic tonnage of 60 EMGTPA. This scenario is generally reflecting a high tonnage urban primary route with high service frequency in terms of commuter flows tied with a significant presence of freight traffic. At high traffic tonnage, following a 60-year appraisal period, the concrete sleepers perform the best by emitting 26-46% less CO_2e compared to the other sleeper variants. Once again hardwood sleepers displayed the second best environmental profile by emitting 16% and 27% less CO_2e over a 60-year period compared to the softwood and steel sleepers respectively (see Figure 4.4). Whereas, the steel sleepers performed the worst due to the carbon intensive nature of their manufacturing process (e.g. 13-46% more CO_2e emissions). Another important consideration that it is worth pointing out is the impact of the selected service lives. For example, when the impact of the service life of the concrete sleepers is taken into account, and their subsequent emissions originating from construction are being normalised on a per km year basis, then it can be seen that these sleepers exhibit the best environmental profile due to their prolonged service life under high traffic tonnage. This highlights that the significantly increased service life of the concrete sleepers under this scenario, results to their EC share being spread out over the examined lifecycle period, as the subsequent amount of renewal operations required will be much smaller than, for example, that of softwood sleepers (e.g. 10-year service life at 60 EMGTPA, translating to five major renewals). Conversely, the significantly reduced service life of the steel sleepers under 60 EMGTPA can explain largely the substantial size of their footprint. The renewal figures from this scenario suggest that the steel sleeper renewal operations emitted 2, 1.8 and 1.5 times more CO_2e emissions compared to these of concrete, hardwood and softwood (see Figure 4.6). Having said this, the literature confirms that this type of sleeper should only be utilised for more lightly trafficked lines and are reported to be suitable only for speeds at or below 160 km/hr (Manalo et al., 2010).

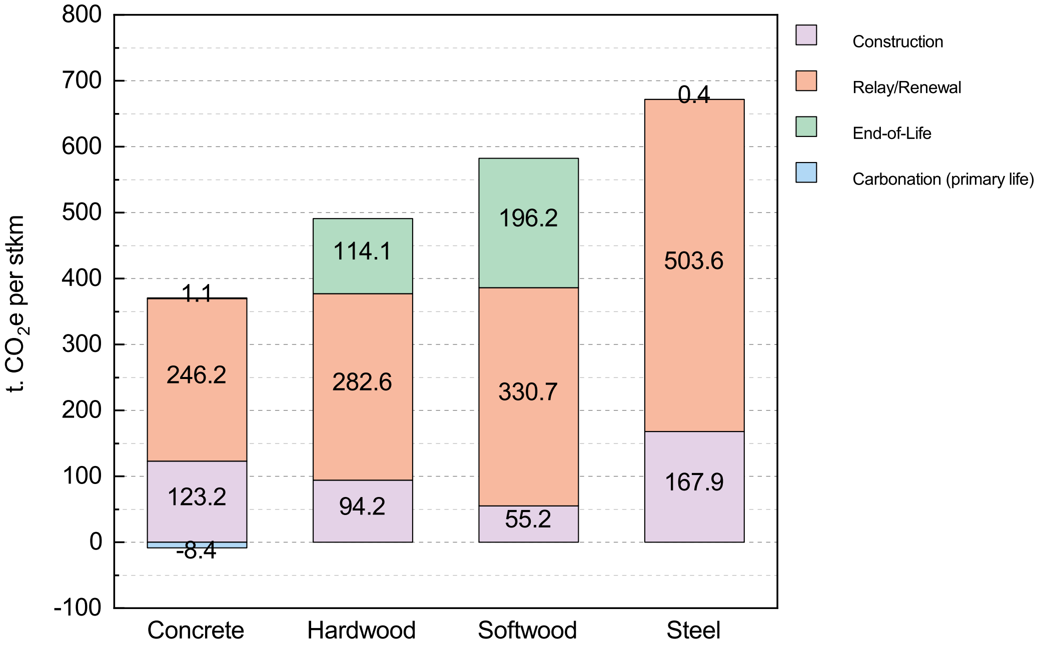


FIGURE 4.6: Carbon footprint for each sleeper type broken down by LCA phase for a 60-year appraisal period (60 EMGTPA) (adapted after Rempelos et al. (2020b)).

Considering the impact of the EoL phase for both the concrete and steel sleepers, it is deemed negligible, accounting for less than 1% of their total footprint. This is marginally greater for concrete, as a proportion by mass of the secondary product is being treated as waste and subsequently, landfilled. In contrast, the impact of disposing the timber sleepers when they become life-expired, results in their footprint being magnified. The figures suggest that the EoL phase for the hardwood and softwood sleepers has a share of 23.2% and 33.7% of their aggregate footprint. This is due to the sizeable releases of CH_4 from landfilling wood, which has 25 times higher GWP when compared with CO_2. The impact from the disposal of timber has been found to be 100 to 180 times higher than that of concrete recycling. When these figures are being compared with the emissions from steel recycling, timber sleepers appear to emit a staggering amount of 325 to 560 times that of steel sleepers. Whilst softwood sleepers have lower mass than the hardwood ones, which would imply a smaller footprint from their disposal phase, their service life difference of 6 years meant that hardwood sleepers have to undergo less frequent interventions (e.g. three complete renewals as opposed to the five relay operations required for softwood sleepers), translating to less waste material ending up on landfill. Once again the carbon uptake of concrete sleepers during their primary life was miniscule (e.g. c. 2.3% of the total footprint).

Taking a lifecycle perspective at this stage, it is important to point out that irrespective of the scenario considered, typically concrete sleepers will last longer, with the high tonnage scenario signifying their advantage in terms of service life. At high traffic tonnage, following 31 years of traffic operation, the concrete sleepers achieve a break-even point resulting in a positive environmental profile compared to the other sleeper alternatives. Their dominance can be better understood by looking at the magnitude of emissions associated with their use, which is comparable with the best steel sleeper scenario at low traffic tonnage (e.g. emitting just about 8.4% more CO_2e compared to the best steel sleeper option). Regardless of the scenario considered the steel sleepers consistently perform the worst. Even at low traffic loads their prolonged service life of 40 years is proven inadequate to offset their sizeable footprint originating from their manufacturing. This is due to the fact that metal products require considerably more processing when compared with concrete or wood products. Adding to this, the production of the appropriate end-products from base steel is also highly energy-demanding, resulting to a sizeable portion of CO_2 emissions. Timber sleepers appear to be a more desirable option from a GHG emissions reduction perspective at least for lightly trafficked routes. Softwood sleepers have the best environmental profile at low traffic loads, while hardwood sleepers display marginally better performance when compared with the concrete ones (e.g. 5.5% less CO_2e).

Scenario 3 : What if scenario? – Timber Incineration

The third scenario was an attempt to examine the amount of incineration with energy recovery required to yield a better environmental profile for both timber sleeper types compared to the concrete ones. Following this scenario, it has been found that a minimum of 50% of the timber sleepers have to be incinerated with energy recovery in order to yield a positive performance. The GHG emissions reduction potential due to the energy recovery process represents approximately 11% (hardwood) and 18% (softwood) of their aggregate footprint (under 60 EMGTPA) (see Figure 4.7). This EoL strategy results to a 7.3% and 12.9% smaller footprint for these variants, when compared to the concrete sleepers (see Figure 4.7). Nevertheless, in reality incineration and/or combustion practices are not suitable due to the toxic chemical compounds including Polycyclic Aromatic Hydrocarbons (PAHs) contained within the timber sleepers due to their creosote impregnation process. Additionally, these processes are also unsuitable from an economic point of view and impractical (Manalo et al., 2010). This is due to the fact that they are treated as hazardous waste and their subsequent disposal and storage is economically unviable compared to ordinary waste.

Comparison of Results

Attempting to compare the overall environmental impact of the sleepers examined in this study against the values found in different studies has proven difficult. This is due to the different methodological assumptions, as well as differences in the drawn SBs and selected FU. However, it was possible to compare the EC emissions from this study against other studies by converting the estimated EC to $kgCO_2e/(sleeper \times year)$ (see Table 4.3).

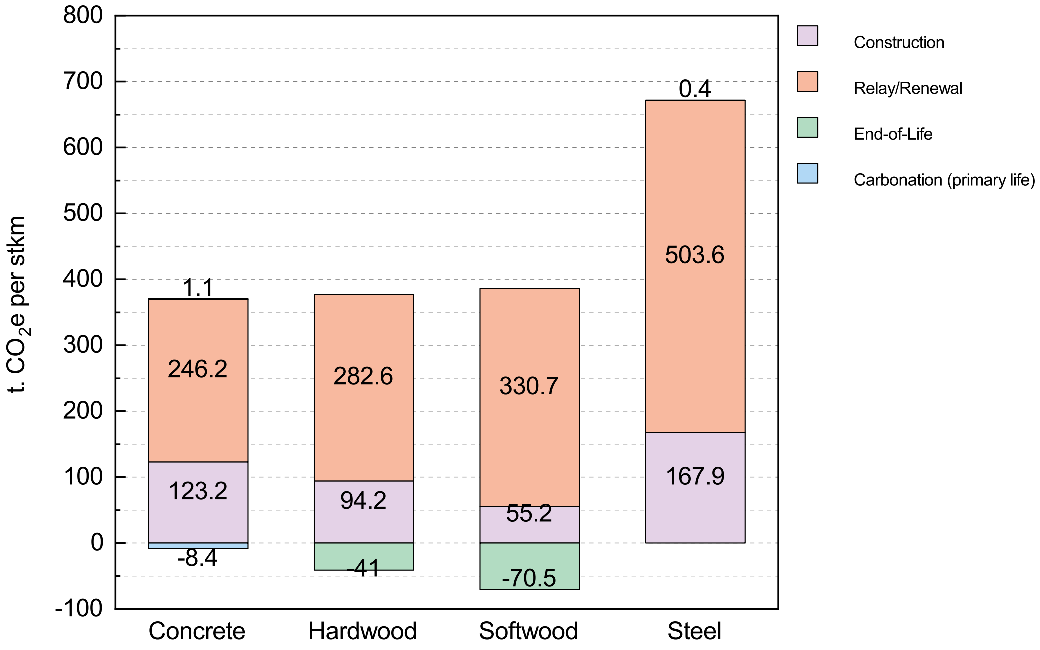


FIGURE 4.7: Carbon footprint for each sleeper type broken down by LCA phase for a 60-year appraisal period (adapted after Rempelos et al. (2020b)).

When comparing the results from this study against the values found by Milford and Allwood (2010), it can be seen that there is a sizeable difference between the emissions for hardwood and softwood sleepers, with the values calculated in the current study being 1.9 and 1.3 greater than the estimates made by Milford and Allwood (2010). This difference is not attributed to the service lives or the mass values adopted as the service lives were drawn from the same source, while the mass values are nearly identical as they apply to country-specific track components. The observed differences between the two studies arise due to the adopted CFs (see Table 4.4). In the present study, the most up to date CFs for both materials have been selected, while the CFs adopted by Milford and Allwood (2010) are being classified by RSSB (2018) as obsolete. Considering the steel sleepers, the current study found the embodied emissions from these sleepers to be 20% smaller than the ones cited by Milford and Allwood (2010). The value for steel sleepers used in the current study is more reliable as it has a specific geographical data coverage for the UK. However, the value adopted by Milford and Allwood (2010) is a global average with unknown scope of coverage. Moreover, the value adopted on this study assumes a 41:59 split of virgin and recycled steel content, while the study by Milford and Allwood (2010) doesn't specify any details on the steel content composition of the analysed sleepers.

When the values of this study are being compared with the predicted values by Ueda et al. (1999, 2003), the differences are significant, as (i) the mass values of the Japanese sleepers are considerably smaller than the respective UK alternatives. Adding to this, (ii) the assumed service lives (e.g. 15 years for timber, 50 years for both concrete and steel) by Ueda et al. (1999,

2003) are different than the ones assumed in the current study (see Table 4.1). Finally, (iii) the CFs for timber sleepers in their study are 0.2 to 0.3 times smaller compared to ones in the current study. Similarly, the steel sleeper embodied factor assumed in this study is approximately 1.7 times the one derived by Ueda et al. (1999, 2003) (see Table 4.4). Finally, comparing the values of this work against the values predicted by Crawford (2009), it can be inferred that there are some sizeable differences. Unlike the study by Ueda et al. (1999, 2003), the observed differences with Crawford (2009) are not predominantly attributed to the mass and service life estimates assumed. These arise mainly due to the difference between the EF estimated in their study, which are 3.8 (for hardwood) and 4.0 times (for steel) higher than the values adopted in the current study. Moreover, unlike this study, the estimated embodied emissions per sleeper, include these of the fastening system, using an EF for virgin steel which is 4.0 times higher than the one estimated in this study.

TABLE 4.3: Comparison of the embodied carbon impact of different sleepers.

Sleeper Component	Ueda et al. (1999, 2003)	Crawford (2009)	Milford and Allwood (2010)		Rempelos et al. (2020b)	
			(10 EMGTPA)	(60 EMGTPA)	(10 EMGTPA)	(60 EMGTPA)
		$kgCO_2e/(s \times yr)$	$kgCO_2/(s \times yr)$	$kgCO_2/(s \times yr)$	$kgCO_2e/(s \times yr)$	$kgCO_2e/(s \times yr)$
Concrete	0.88	4.68-7.80 (50/30 yrs)	1.91	3.59	1.8	3.3
Hardwood	0.75	18.53-27.80 (30/20 yrs)	0.91	2.06	1.7	3.8
Softwood		n/a	0.75	2.71	1.0	3.6
Steel	0.96	n/a	3.30	7.76	2.7	6.4

TABLE 4.4: Comparison of the embodied CFs adopted in this study against the values adopted in other studies.

Sleeper Component	Ueda et al. (1999, 2003) $kgCO_2/kg$	Crawford (2009) $kgCO_2e/kg$	Milford and Allwood (2010) $kgCO_2/kg$	Rempelos et al. (2020b) $kgCO_2e/kg$
Concrete	0.285	0.225	0.28	0.256
Hardwood	0.198	3.27	0.47	0.87
Softwood		n/a	0.45	0.59
Steel	0.873	5.85[1]	1.77	1.46

[1] EF refers to 100% virgin steel fastening as steel sleepers were not appraised.

4.3.2.3 Sensitivity Analysis

Following the initial appraisal, a sensitivity analysis has been performed using a One-at-a-Time technique (OAT). This localised approach enabled the input parameters to be changed one-at-a-time in order to investigate their influence on the final result. Using this method and given the results from the literature review, seven factors were tested for both the high and low load traffic scenarios. These were: the impact of the service life (±30%); sleeper spacing (US and Australian specifications); transport distance (+100-300%); amount of sleepers incinerated with energy recovery (+75-100%); gate-to-site transport mode (modal shift from rail-to-road and *vice versa*); proportion of virgin and recycled steel used (±100%); and productivity of installation equipment (±50%) (see Figure 4.8).

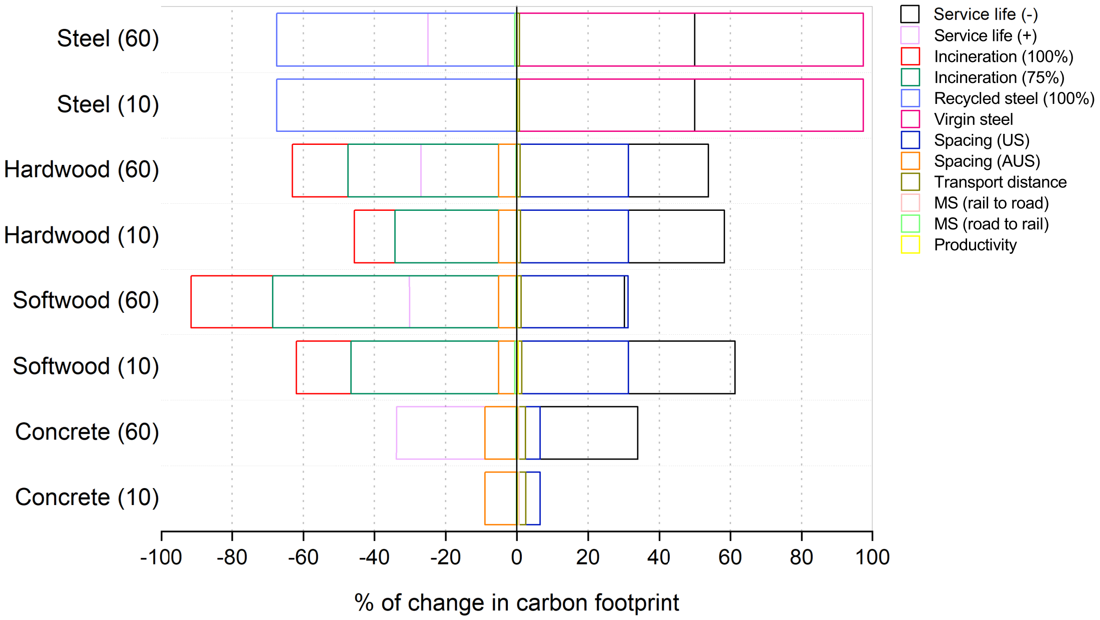


FIGURE 4.8: Sensitivity analysis – Tornado chart (adapted after Rempelos et al. (2020b)).

Based on the results of Figure 4.8, a number of conclusions can be drawn. First, at low traffic loads, regardless of the magnitude of overestimation softwood sleepers will consistently exhibit the best performance. On the contrary, by assuming that the service life of hardwood sleepers is overestimated by more than 20%, results in their performance being the worst compared to softwood and concrete. At high traffic loads, concrete sleepers perform the best even by assuming a 30% overestimation of their service life, while an overestimation of 10% of the service life of hardwood would result in the softwood sleepers outperforming them.

Second, the choice of EoL pathway for timber sleepers can reshape their footprint as irrespective of the traffic load scenario examined, these variants outperform both concrete and steel sleepers when a minimum of 50% them follows the combustion pathway with energy recovery. Similarly, although it may not be realistic in practice, the use of 100% secondary steel will result in the steel sleepers outperforming all other variants, regardless of the traffic load scenario examined.

Third, both gate-to-site transport distance and mode choice have an impact to the lifecycle emissions of these structures, but it is deemed negligible compared to their total footprint. For example, the mode choice appears to have an impact of less than 1%. Equally, even by increasing the transport distance for all materials from 50 to 200 km results to an increase of about 0.7 to 2.5% of the total footprint of the examined structures. Similarly, by overestimating the productivity of construction equipment by as much as 50%, will have an impact of $<1\%$ on the lifecycle emissions of these sleepers.

Finally, as it is expected the use of Australian track standards has a considerable impact in the carbon footprint of both timber (-5%) and concrete (-9%) sleepers due to the wider spacing requirements (685 mm and 714 mm), resulting in less sleepers installed per stkm. On the contrary, the adoption of North American standards, results on an increase of about +7% of the footprint of concrete sleepers due to the tighter spacing intervals of Class 1 mainlines in the US. This effect is even more pronounced for timber sleepers (+31%), where the spacing is around 495 mm compared to an equivalent 650 mm for UK routes, resulting to an additional 482 sleepers installed per stkm.

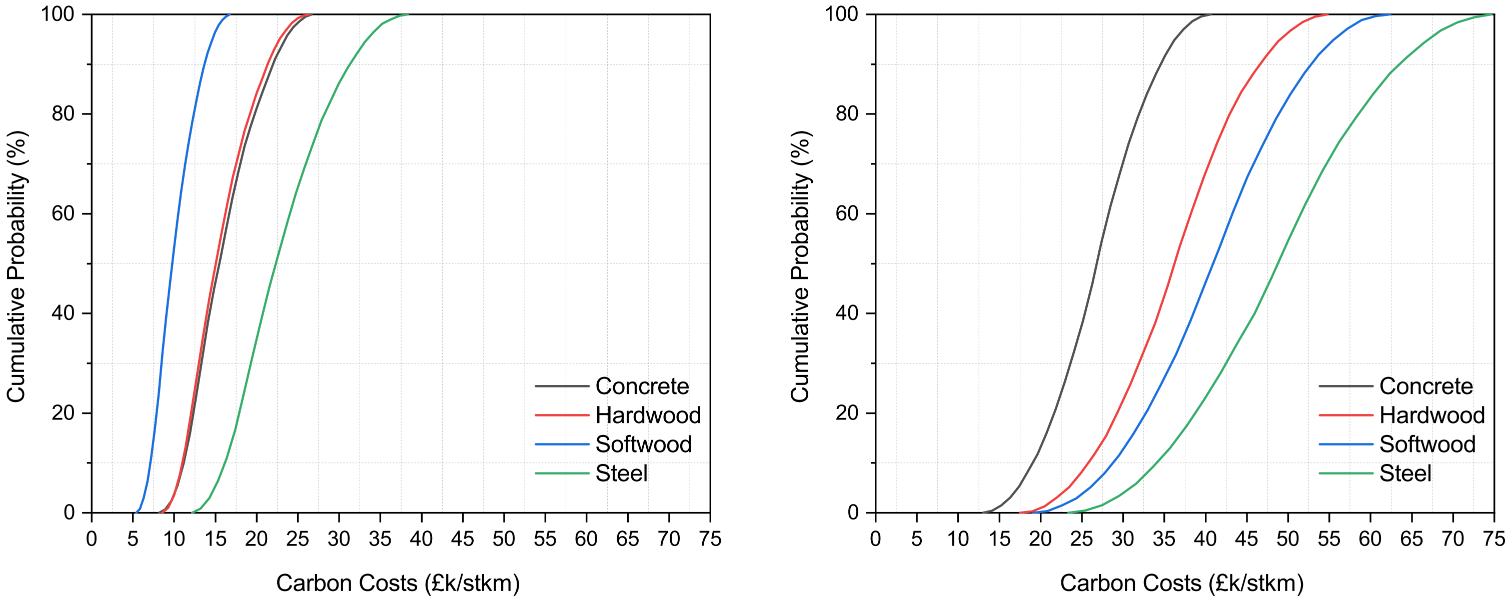
4.3.2.4 Carbon Footprint Costs

Once the GHG emissions resulting from each scenario have been quantified, these are given a monetary value. In valuations for appraisal, the UK government adopts a target-consistent approach, basing this on estimates of the abatement costs required so as to meet specific emissions reduction targets. Considering this, the carbon values given by the DfT (2019) are used to monetise the changes in emissions from each option. It is worth noting that these values have been increased recently (as of May 2022), given the climate emergency. However, these changes are expected to have a negligible impact in the results of this study.

Considering the high traffic load scenario, the use of concrete sleepers, instead of hardwood, softwood, or steel can bring about a benefit of £9,436, £13,886, or £22,231 per stkm, respectively. Conversely, for the low traffic load scenario, the choice of the softwood variant results in a welfare benefit of approximately £4,377 to £10,304 per stkm, depending on the sleeper variant they substitute. For these calculations, the base year for discounting is 2019, with the base test discount rate taken as 3.5% for the first 30 years of the appraisal and a lower discount rate of 3.0% used thereafter (as recommended by HM Treasury (2018)).

It is worth highlighting that there are some inherent risks associated with the economic evaluation of the costs of CO_2e on this study. Thus, in order to overcome this, a stochastic approach has been selected, instead of a deterministic one. This has been done by conducting a MCS (Kalos and Whitlock, 2008). The goal of the adopted methods was to assess the risk associated with these estimates, choosing randomly modifiable values in each iteration. In terms of simulation details, MCS samples were of size 10,000 for each of the models. It was assumed that the evaluated annual cost of carbon is a triangularly-distributed random variable; with the minimum, maximum, and mode being calculated based on the target-consistent marginal abatement costs given as a three-point estimate by DfT (2019). The cumulative probability distribution curves for each sleeper variant (and load scenario) are displayed in Figure 4.9 below.

A number of conclusions can be drawn from the results of the MCS presented in Figure 4.9. First, for the lower tonnage routes the expected lifecycle carbon costs for each sleeper type are considerably lower than those for the higher track category routes. Additionally, for the latter route scenario, there is a higher uncertainty for these cost estimates as it can be inferred from the higher width, and flatness of their S-Curves, indicating higher standard deviation (σ). Second, at high traffic loads, there is a clear difference in terms of carbon costs between each sleeper type, with the concrete sleepers bringing the lowest minimum (£12.8k/stkm) and maximum (£40.7k/stkm) carbon cost per stkm compared to the other three variants. Third, for the lower track category routes, the softwood sleepers, have the lowest carbon costs, both in terms of minimum and maximum possible value, with a higher certainty around these estimates, as indicated by the lower value of σ. Then again, for the case of concrete and hardwood sleepers, there is an evident overlap between their S-Curves. Considering this, the former brings a lower minimum cost (£8.1k/stkm (concrete) $<$ £8.5k/stkm (softwood)), whereas, its maximum possible value is marginally greater than that of the latter (£26.8/stkm (concrete) $>$ £26.4k/stkm (softwood)). Finally, under high traffic loads the expected carbon costs for the best performing variant (concrete) can be set between £18.9k to £34.6k/stkm with an 80% probability, and an μ value (population mean or expected value) of £26.8k/stkm. Whereas, under the same route scenario, the second best performing alternative (hardwood) will have its carbon costs set between £25.8k to £46.7k at the same probability, and an μ value of £36.2k/stkm. While, for the low traffic load scenario, the best performing variant (softwood) will have its carbon costs set between £7.3k to £13.6k per stkm (80% probability), and an μ value of £9.9k/stkm.



(A) 10 EMGTPA

(B) 60 EMGTPA

FIGURE 4.9: Costs of carbon dioxide cumulative distribution function (for each sleeper variant), [A]: Low tonnage scenario [top], [B]: High tonnage scenario [bottom] (adapted after Rempelos et al. (2020b)).

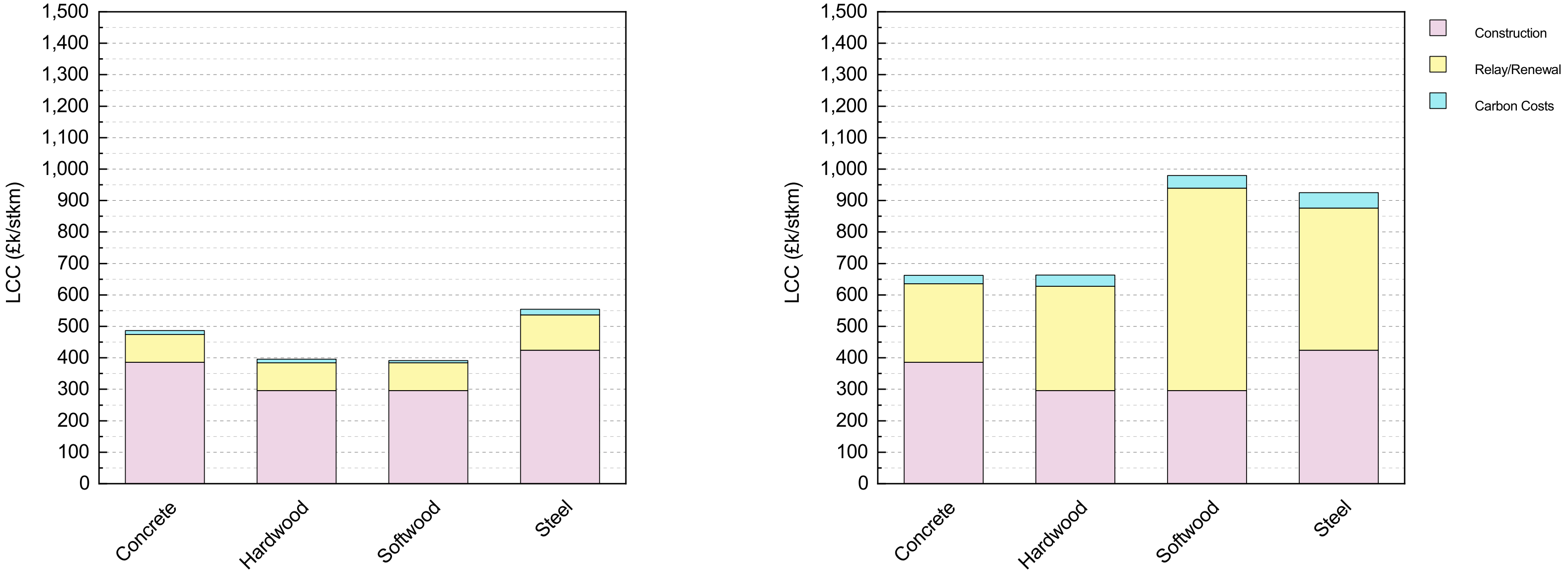
4.3.3 LCCA Modelling Results

So as to examine prospective trade-offs between the one-off and the on-going financial and environmental externalities throughout the useful life of these structures, their LCC were calculated for each scenario. Other elements of the wider social cost such as the impact of air-borne and ground-borne noise have been excluded as data was not readily available. Accordingly, this calculation included only the direct activity costs of each sleeper variant (materials, transport, plant, and time-on-tools labour hours) excluding any indirect costs or overheads, these were sourced directly from NR in 2017/18 prices as per Control Period 5 (CP5: 2014 to 2019). These cost elements were grouped at the standard job activity level and adjusted for inflation since original estimates, using the Consumer Price Index (CPI) based GDP-deflator sourced from the DfT (2019). This conversion is equivalent to multiplying the annual values based in 2017/18 prices with the value of CPI based GDP-deflator in 2019 (103.920) over the baseline value of 2017 (113.920/100 = 1.0392). This implies that over a two-year period the prices have gone up by 3.92%. It is worth noting, that the productivity values for different activities are not constant over time and may require adjustment, however, for the purposes of this research, these have been assumed constant over time as per CP5 estimates (Williams, 2018). Once again, for these calculations the base year for discounting is 2019, with the base test discount rate taken as 3.5% for the first 30 years, and a lower discount rate of 3.0% used thereafter. The results of the LCC analysis broken down by cost type for each simulated load scenario are displayed in Figure 4.10.

Some conclusions can be drawn from the results of the LCC analysis presented in Figure 4.10. First, irrespective of the sleeper variant or traffic scenario examined, the costs of carbon are small compared to CapEx and OpEx of these structures over a 60-year period, representing just about 1.9-5.5% of the total LCC, depending on the sleeper variant and scenario examined.

Second, for a high traffic tonnage scenario, the concrete sleepers appear to outperform the remaining variants, with the associated benefits of choosing concrete sleepers as opposed to softwood or steel, being approximately £317,790/stkm and £263,639/stkm, respectively. However, these savings are considerably lower when substituting hardwood sleepers, with the equivalent figure being just about £1,487 per stkm. Conversely, for a low traffic tonnage scenario, softwood sleepers outperform all other options in terms of LCC, with the savings per stkm (over a 60-year period) being at c. £95,234 and £163,452 compared to the concrete and steel sleepers, respectively. Once again, hardwood sleepers perform marginally worse than the best performing alternative, with the LCC savings per stkm of the softwood variant compared to hardwood being just around £4,377.

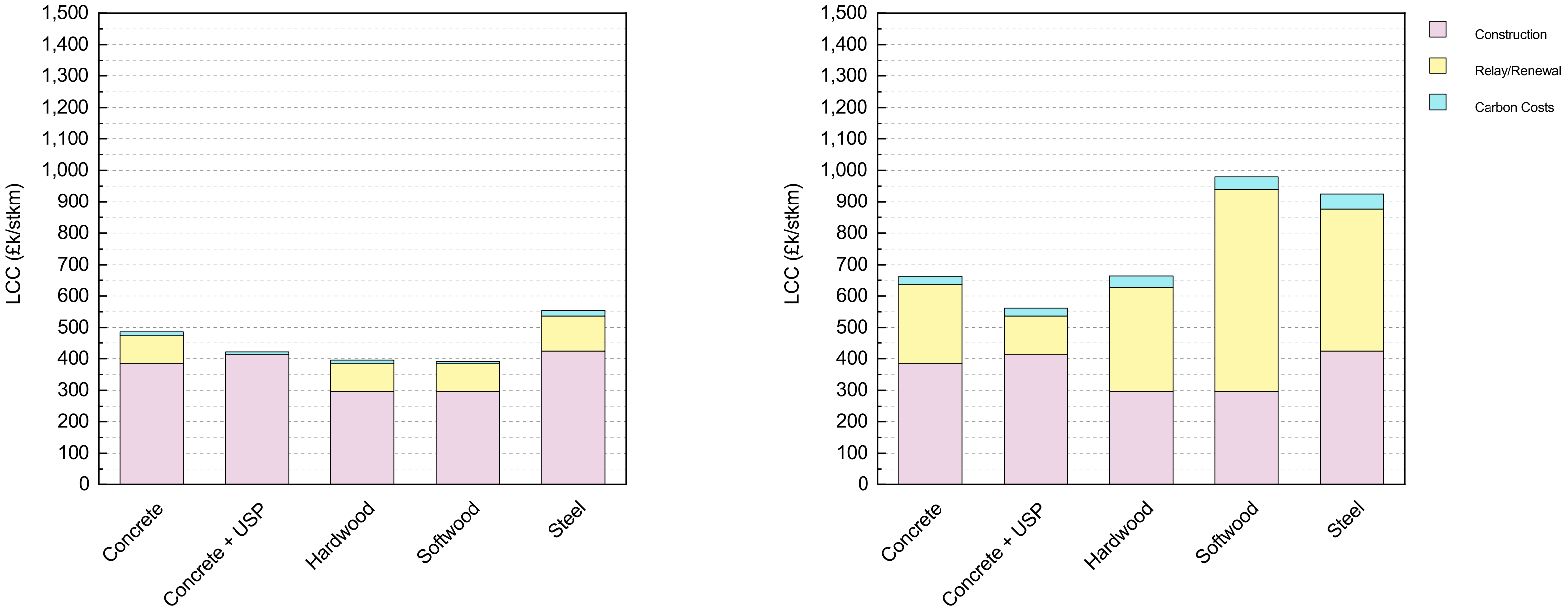
Third, for the low traffic tonnage scenario, CapEx is the highest contributor to the LCC regardless of the sleeper variant, with this phase accounting between 74.7% and 79.2% of the WLCC. In contrast, for the high traffic scenario, the share of OpEx dominates the WLCC for all variants (c. 48.9-65.7%) apart from the concrete sleepers. Considering the latter, their CapEx share is approximately 58.3%, compared to an equivalent 37.7% attributed to ongoing expenditure by the IM. This result is partly due to the greater service life of these sleepers, translating to fewer interventions compared to the remaining variants, but also due to the heavy discounting used, placing heavier weight on the investment made during the earlier years of the appraisal.



(A) 10 EMGTPA

(B) 60 EMGTPA

FIGURE 4.10: LCC (2019 prices) of each sleeper variant for a 60-year appraisal period broken down as CapEx, OpEx, and cost of carbon for a low [A] and high traffic tonnage scenario [B] (adapted after Rempelos et al. (2020b)).



(A) 10 EMGTPA

(B) 60 EMGTPA

FIGURE 4.11: LCC (2019 prices) of each sleeper variant, including the scenario of concrete sleepers with USPs fitted for a 60-year appraisal period broken down as CapEx, OpEx, and cost of carbon for a low [A] and high traffic tonnage scenario [B] (adapted after Rempelos et al. (2020b)).

Scenario 4 : Installation of Concrete Sleepers with USPs

In the course of the second half of CP6 (2019-2024), concrete sleepers are anticipated to be in routine production with USPs in the UK. A USP is a highly elastic (resilient) element attached underneath the sleepers, so as to provide an intermediate elastic layer between the sleeper and the ballast. Made from polyurethane, rubber, Ethylene-Vinyl Acetate (EVA), USPs were first developed in the 1980s and are widely used across Europe but not in the UK, other than on London Underground.

The IM expects concrete sleepers fitted with USPs to last 50% longer than the in-service concrete variants, for an additional cost of £15/sleeper (in 2009 prices) or £17.8/sleeper (in 2019 prices). Against this background, an additional scenario of installing concrete sleepers with USPs (stiff 4-mm thick) was simulated, resulting in an additional cost of £27k/stkm (c. £22-23k/stkm in 2009 prices) representing a cost increase in material supply per stkm of between 26% and 32% (to the present-day sleeper cost), and a carbon surplus of $49.76t.CO_2e$ for installing USPs per km of single track.

The simulated scenarios assumed that the inclusion of USPs prolong the concrete sleeper service life by 50% (for example, for the high traffic load scenario, from 24 to 36 years). Based on this analysis (Figure 4.11), the inclusion of USPs will improve the economic profile of concrete sleepers over a 60-year period by c. £65,000 to £100,000 per stkm, as well as an equivalent carbon saving of about $23\text{-}73t.CO_2e$ per stkm, depending on the load scenario examined. These improvements are in effect due to the enhanced service life of the concrete variant, reducing the number of interventions required over the examined lifecycle, but also delaying the time of initial investment for track relay by 12 (high) to 23 years (low), depending on the examined route. Finally, by assuming the installation of carbon-neutral USPs, these carbon savings would rise up to about $122t.CO_2e$ per stkm for both the low and the high tonnage route. Considering this, recycled, life-expired road vehicle tyres can be an appealing option for treatment, and subsequent use as USPs (Sol-Sánchez et al., 2014), while maintaining the track at an adequate track quality standard (Sol-Sánchez et al., 2016).

4.4 Conclusions

This study evaluated and compared the lifecycle GHG emissions associated with the four most common sleeper types present in the UK railway network. It estimates the embodied material, process and transport emissions linked with the lifecycle activities of construction, relay and EoL of these variants at low and high traffic loads. Based on the results of this chapter the following conclusions can be drawn.

Firstly, under the low traffic scenario, the softwood sleepers appear to be the most favourable option from a GHG emissions point of view. In contrast, at high traffic loads, the concrete sleepers are preferred as their prolonged service life results in their sizeable embodied emissions' share being spread out over the examined lifecycle period, this means that the volume of required interventions will be much smaller than, for example, that of softwood sleepers. The analysis revealed that the already burdensome footprint of steel sleepers is being magnified at high traffic loads, primarily, due to their unsuitability for heavy trafficked applications. The renewal figures from this scenario suggest that the steel sleeper interventions emit almost twice more CO_2e compared to the other variants.

Considering timber sleepers, it has been found that the choice of EoL pathway following life-expiration is a critical factor of their environmental performance. Depending on the scenario selected the EoL phase of hardwood and softwood accounts for between 17% and 33.7% of their footprint. When these impacts are compared with the associated impact of steel and concrete recycling, the figures suggest that timber landfilling result in 100-180 times higher GHG emissions compared to that of concrete recycling and a remarkable amount of 325-560 times more CO_2e emissions compared to that of steel recycling. Nevertheless, it has been shown that if a minimum of 50% of the timber sleepers follow the combustion pathway with heat recuperation, then a GHG reduction potential of between 11% and 18%, measured as a percentage share of their total footprint can be realised. Finally, despite the inclusion of concrete's carbonation during its primary life, the effect of this phenomenon has been confirmed to be negligible, accounting for less than 3% of its overall footprint. Nonetheless, it is believed that the carbon uptake of the recycled downstream concrete products during their secondary life can be significant, thus, it is recommended to scope in this activity in future analyses.

This work also included an LCC analysis of these sleepers. Based on the results the following conclusions can be drawn. First, irrespective of the sleeper variant or traffic scenario examined, the costs of carbon are small (representing 1.9-5.5% of the total LCC) compared to the lifecycle CapEx and OpEx of these structures. Second, for a high traffic tonnage scenario, the concrete sleepers appear to outperform the remaining variants, displaying benefits of up to £317,790/stkm; whereas, for a low traffic tonnage scenario, softwood sleepers result on a maximum WLCC saving of £163,452/stkm, with this varying depending on the variant they substitute. Finally, by installing concrete sleepers fitted with stiff USPs at high tonnage routes, their expected benefits are magnified. Based on these results, the inclusion of this intervention will achieve additional LCC savings in the magnitude of c. £65,000-100,000 per stkm of installation, and an equivalent reduction in their carbon footprint of about 23-73$t.CO_2e$/stkm, depending on the annual tonnage of the route. Then again, it has been shown that the use of carbon-neutral USPs can amplify these savings even further, offering a more appealing option from an environmental viewpoint.

Chapter 5

Case Study II: Asset appraisal

5.1 Introduction

Most applications of railway infrastructure LCA and LCCA have focused exclusively on modelling plain track, while disregarding entirely more complex sections of a route, such as for example, Switches and Crossings (S&Cs). This scarcity of available studies (see Section 2.6.5) is due to the complexity of these layouts, as well as the heavy data and modelling requirements for carrying out such appraisals. Nevertheless, quantifying the environmental impact of these sections is a crucial basis for constructing more detailed route models so as to examine the impact of different railway track interventions.

This chapter therefore builds upon the modelling framework presented in Chapter 4, extending its capabilities by integrating a detailed LCI, which is tailored around some of the most common S&C designs used in the UK (see Figure 3.6). This whole life carbon model permits the 'cradle-to-grave' appraisal of different S&C design variants. This is done by an exemplar case study.

First, a modelling framework is developed for environmental and financial appraisal both at an asset and component level. Second, the applicability of the model is tested through an environmental and economic case study of fifteen of the most common S&C (six turnouts and nine crossovers) design variants present in the UK railway network. While the conclusions from this chapter will be only directly applicable for the SBs of designs manufactured in the region of Great Britain, the modelling framework developed could be easily transferred to other geographic regions, and could therefore play a significant role in efforts to further reduce rail's environmental impacts around the world.

5.2 Methodology

5.2.1 Scope

Given the above, this chapter critically appraises and compares the life cycle environmental impacts associated with fifteen S&C (six turnouts and nine crossovers) design variants present in the UK railway network (see Table 5.1).

TABLE 5.1: Overview of S&C design variants examined.

Code	Rail type [1]	Switch size [2]	Crossing angle	Layout
NR 56	CEN 56 vertical	BVs	8	Turnout
NR 56	CEN 56 vertical	CVs	13	Turnout
NR 56	CEN 56 vertical	CVs	13	Crossover
NR 56	CEN 56 vertical	DVs	15	Turnout
NR 56	CEN 56 vertical	DVs	15	Crossover
NR 60 Mark 1	CEN 60	C	11	Crossover
NR 60 Mark 1	CEN 60	D	13.5	Crossover
NR 60 Mark 1	CEN 60	E	17.25	Turnout
NR 60 Mark 1	CEN 60	E	17.25	Crossover
NR 60 Mark 2	CEN 60	C	13	Turnout
NR 60 Mark 2	CEN 60	C	13	Crossover
NR 60 Mark 2	CEN 60	D	10.75	Turnout
NR 60 Mark 2	CEN 60	D	15	Crossover
NR 60 Mark 2	CEN 60	E	18.5	Crossover
NR 60 Mark 2	CEN 60	E	21	Crossover

[1] Numerical value is equivalent to the weight of the rail per metre.

[2] Letter classification is used for signifying certain turnout lengths and radii.

Broadly speaking, the most commonly quantifiable environmental impacts when it comes to the appraisal of railway infrastructure assets are indicated by the GHG emissions and energy consumption. For this analysis, a VBA excel spreadsheet model has been developed to evaluate the carbon footprint of different S&Cs by adopting a life cycle approach and the results are presented using a CO_2e metric.

The subsequent evaluated emissions have been normalised by design type and also over a *metre* of track ($t.CO_2e$ per m), to permit the summation of the environmental impacts of the processes modelled within their life cycle. The latter metric was also adopted to allow for comparisons to be made between variants. The key processes included in this analysis are broken down in the following core phases of the infrastructure's life: construction, maintenance, relay/renewal and EoL, with the associated emissions being based on the devised table of EFs. The methodology adopted in this work is based partially on the framework described by the conceptual LCA framework guidelines designated by the ISO (2006a,b) and BSI (2011, 2016).

5.2.2 Switches and Crossings

5.2.2.1 Overview

Historically these sections have taken about 23% and 24% of the renewal and maintenance budgets against a 5% of representative track miles, mainly due to complex wheel to rail interactions and machined longitudinal rail profiles (Cornish, 2014). To better understand the magnitude of these costs, in the FY 2009/10, NR spent around £32 million on failures within S&Cs, where 53% of these emerged within the switch panel (Cornish et al., 2016). Any failure typically leads to operational delays and service cancellations, which often propagate rapidly where no wider diversionary route is available (Bemment et al., 2017, 2018), affecting negatively the quality of service delivered, railway safety, and also operating costs (Rama and Andrews, 2013). Typically, S&Cs are responsible for around 10% of the network delays (Cornish, 2014), with equivalent statistics for the period between FY 2007 – 2012 suggesting a percentage share of 18.3%, which is just 0.5% less than the equivalent minutes of delay caused by the rest of the permanent way (Bemment et al., 2018). This may not seem as large, but when considering the financial losses for compensation of unscheduled downtime to the operators, then these issues become increasingly evident. Indeed for compensation payments alone, NR spends approximately £26 million per FY.

Typically, an S&C will be replaced after between 25 to 60 years, depending on the speed and tonnage of the route. For high-speed routes (>128mph, or 25 EMGTPA) the expected life is about 25 years, reflecting 2.1% of the asset population. Whereas, their useful life grows incrementally up to the 60 – year mark for lower speed/tonnage routes (25 mph, or 6 EMGTPA), accounting for 23% of the population (Cornish, 2014). These assets are both safety and performance critical, enabling vehicles to:

- Manoeuvre between various tracks to continue their way in different directions;
- Join multiple tracks or to split up a single track into multiple track;
- To change tracks but continue in the same direction on different lines;
- To cross other tracks.

These functions permit trains to either travel in various directions to other destination, manoeuvre an obstruction, or enhance capacity by finding new sections of rail to run along. These can be completed through different layout configurations. The primary layout types include: turnout, crossing, crossover, and slips (either single or double). Of these layouts, the most common is that of a turnout (Figure 5.1). A standard turnout can be broken down into three panels: the (i) switch, (ii) closure, and (iii) crossing panel. Each of these can be further broken down to each constitutive components (see for example, Figure 5.2).

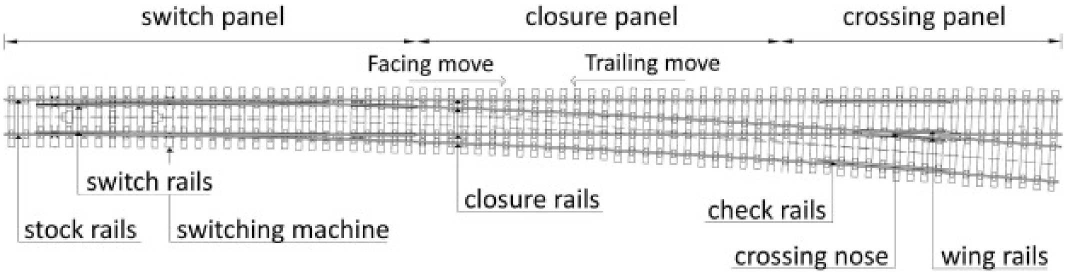


FIGURE 5.1: Design and component nomenclature of a standard turnout. Sources: Fellinger et al. (2020)

1. Fixed stretcher bar
2. Left hand stock rail
3. Left hand switch rail (closed)
4. Lock stretcher bar
5. Right stock rail
6. Right switch rail (open)
7. Baseplates
8. Sleeper / bearer
9. Switch spacer block
10. Heel block
11. Transition
12. Switch tips

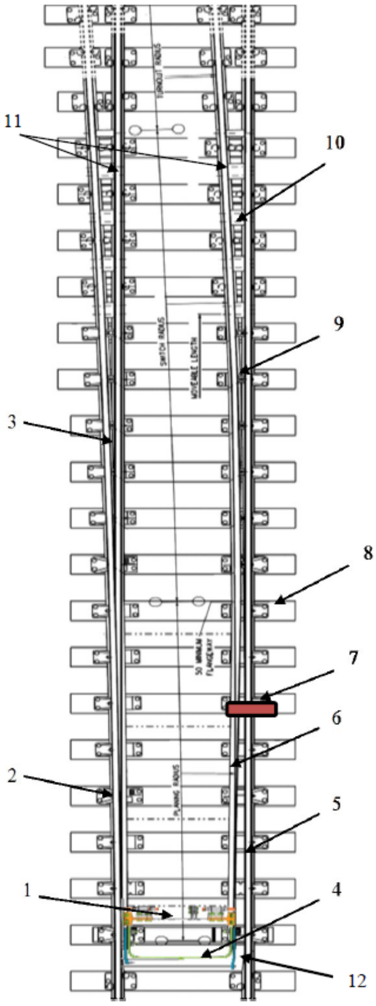


FIGURE 5.2: Components of a common switch unit in the through direction. Sources: Cornish (2014)

5.2.2.2 Design variants

The design variants examined in this chapter (Table 5.1) can be broken down in three design families: (1) NR 56 vertical, (2) NR 60 Mark 1, (3) NR 60 Mark 2. The first difference between the benchmark design (e.g. NR 56 vertical) and the Mark 1 and Mark 2 is that the latter use CEN60 rail sections, which are taller and therefore, stiffer than the CEN56 (Bostock, 2021). Moreover, with CEN60 designs the bearer spacing is tighter (650 mm vs 710 mm) than that of vertical designs. Additionally, the running rails are inclined (as opposed to vertical) and the gauge is 1435 mm, which leads to better wheel rail interaction (Bostock, 2021). Crompton and Bostock (2017) and Bostock (2021) summarised the following benefits of CEN60 compared to CEN56/54 vertical designs:

- Combination of taller rail and tighter spacing offers a stiffer track form, which results to reduced loading on the ballast and formation, leading to better support conditions.
- Combination of inclined running rails and the 1435 mm gauge, result to better wheel rail interaction, and thus, less RCF.
- They offer lower bending stresses in the rail, resulting to less rail defects.
- Better vehicle dynamics, resulting to improved steering characteristics and higher vehicle stability.
- Crossings have on average a longer life, with a lower risk of fatigue cracking (from the base).

The first UK design using a CEN60 rail section, was the RT 60, which was developed in the late 1990's. Four variants (Edgar Allen, Balfour Beatty, Corus Cogifer, VAE) have been designed, each of these was delivered by the NR manufacturers with manufacturer specific components, but with common layout geometry and crossing footprint (as specified by NR guidelines) (Bostock, 2021). However, some of the issues with these newly found designs, were that their geometry differed from their predecessor (NR 56 vertical designs) and their switches used a higher cant deficiency limit (Bostock, 2021).

In an attempt to address some of these issues and rationalise these into a single design, NR bought the rights to the Edgar Allen RT 60 (in 2005 to 2006) and by introducing some minor changes, they developed the NR 60 Mark 1 (Bostock, 2021). However, this design introduced some further challenges, particularly with respect to cost and also geometric footprint compatibility, particularly for the case of like-for-like replacements, which were often not possible due to their incompatibility (in terms of geometry) when they had to replace older designs (NR 56/54 vertical designs) (Bostock, 2021). Other problems also included, crossing issues as well as switch wear and damage.

This geometric incompatibility with NR 56 v designs (among other issues) led to the development of the NR 60 Mark 2 design. Aside of the benefits listed earlier, this design offers (Bostock, 2021):

1. Better profile, wheel transfer.
2. Lower dip angle and impact forces.

3. High resilience of the crossing as shown from design and stress analysis.

However, certain issues remain, for example, similarly to Mark 1 a high peak load (smaller than Mark 1) occurs on the steering switch. Concluding, there are also important challenges with respect to costs. According to Bostock (2021), NR 56 v has become the benchmark for cost and NR 60 will always cost more. At present NR 60 Mark 2 have a unit rate for materials, which is higher by 15 – 25% (Bostock, 2021). Moreover, as new installation are usually first off, the set up costs are high (Bostock, 2021). Finally, due to the unfamiliarity of the supply chain (suppliers, manufacturers), there are also initial contingency costs (Bostock, 2021).

5.2.3 Inventory Analysis and Functional Unit

The SB selected for the inventory analysis has been summarised in Figure 5.3, the shaded processes represent the upstream and downstream stages which are not scoped in the appraisal. It should be pointed out that the in scope activities, CFs, geographical coverage boundaries and track specifications adopted are chosen to represent the UK region.

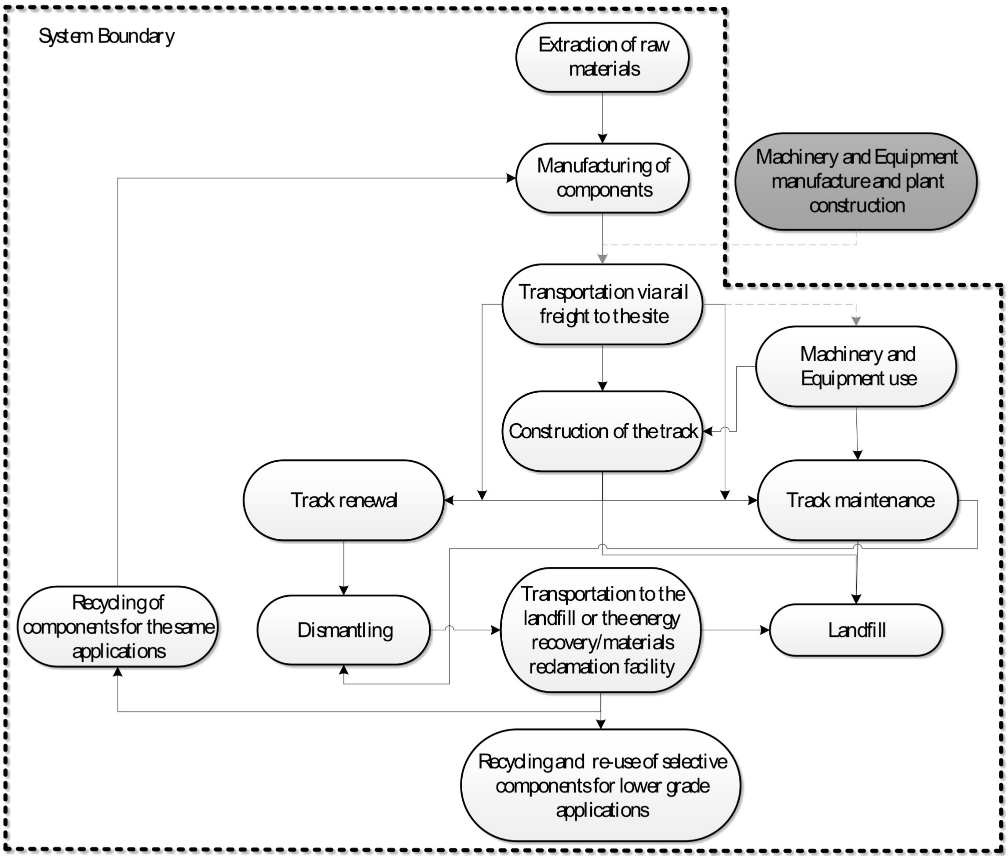


FIGURE 5.3: Simplified flow diagram and associated SB for the LCA carbon footprint model.

As already discussed, the environmental indicator metric of this appraisal is CO_2e, with the associated emissions being normalised per design variant.

Considering the lifecycle adopted for this study, a 60-year appraisal period has been chosen in line with WebTAG recommendations (DfT, 2018), with the associated in scope processes being the raw material extraction, manufacturing of track components, transport of materials on site by road or rail freight, transport of labour and plant on site, infrastructure use (e.g. repair, maintenance and renewal activities, etc.) including the dismantling of obsolete components and the subsequent relay/renewal of new ones and finally, the EoL phase of life-expired components following the appropriate downstream pathway.

5.2.4 Model construction

5.2.4.1 Embodied Emissions

The EC impact of the construction phase for each examined track component was estimated based on their material properties and carbon intensity values. The embodied CO_2e emissions, EC_j^{c-g} 'cradle-to-gate' associated with the manufacturing of each component were estimated by multiplying each material mass with the associated CF (Equation 5.1). These CFs are based on the Bath Inventory of Carbon and Energy (Hammond and Jones, 2011, 2019) and the RSSB's Rail Carbon Tool (RSSB, 2018).

$$EC_j^{c-g} = \sum_{i=1}^{n} M_i \times C_i \times CF_i \tag{5.1}$$

Where, EC_j^{c-g} is the aggregate embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for component j in $kgCO_2e$; i is the material index; n is the total number of materials used in the construction of track component j; M_i is the mass of material i for each component given in kg; C_i is the % composition of each material to the total mass of the component; CF_i is the EC factor for each material i given in $kgCO_2e/kg$.

The embodied emissions, EC_k^{c-g} 'cradle-to-gate' associated with the manufacturing of each panel were then estimated using Equation 5.2.

$$EC_k^{c-g} = \sum_{j=1}^{n} EC_j^{c-g} \tag{5.2}$$

Where, EC_k^{c-g} is the embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for panel k; EC_j^{c-g} is the aggregate embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for component j in $kgCO_2e$; n is the total number of components j per panel k for each design.

Then the embodied emissions, EC_i^{c-g} 'cradle-to-gate' associated with the manufacturing of each design variants can be estimated as follows (Equation 5.3).

$$EC_i^{c-g} = \sum_{k=1}^{n} EC_k^{c-g} \tag{5.3}$$

Where, EC_i^{c-g} is the embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for design variant i; EC_k^{c-g} is the total embodied 'cradle-to-gate' $(c-g)$ CO_2e emissions for panel k in $kgCO_2e$; n is the total number of panels k for each design variant.

TABLE 5.2: Railway track component LCI inclusions and exclusions, including data sources.

Category	Component inclusions	Source for activity data
Rails	incl. stock, wing, vee, check rails	Progress Rail[1,2]
Rail support	incl. fastening, baseplate, rail pad	Progress Rail[1,2]
Miscellaneous	incl. screws, washers, fishplates, joints, insulators, etc.	Progress Rail[1,2]
Switch	incl. switch rails, locking device, hollow sleeper	Progress Rail[1,2]
Crossing		Progress Rail[1,2]
Bearers	various dimensions	Progress Rail[1,2]
Sleepers	same as above	Progress Rail[1,2]
Sleepers support	incl. USP	Progress Rail[1,2]
In Bearer Clamp Lock (IBCL)		Progress Rail[1,2]
Ballast		Abadi et al. (2018)
Sub-ballast		

[1] Edwards, M., 2021. Personal communication (Progress Rail).

[2] Peet, D., 2022. Personal communication (Progress Rail).

The LCI created for this chapter is of high granularity level (see Table 5.2 for an overview of the components included) and it was created by following bottom-up principles, using as input data, information from AutoCAD drawings for each design variant, including details in the form of BoM and BoQ, both of which were provided by Progress Rail, which serves as the primary supplier for NR. A bottom-up approach was selected in order to ensure robustness by relying exclusively on UK network-specific supply chains and production processes.

5.2.4.2 Component Processing

The plant and machinery emissions arising during track installation processes (e.g. construction, complete renewal, etc.) have been estimated for each design based on the number (and mix) of machines and the time spent on site (as an example, see Table 5.3). First, the mix and number of machinery and plant required for the installation and renewal processes of an NR60 FV 1 in 21 Turnout and Crossover have been sourced from a template by RSSB (2018). These hourly requirements have been then scaled for each design variant based on the number of panels to be installed or renewed in each case. It is worth noting, that for the case of renewals (complete renewal, ballast, sleeper/bearer or rail renewal), additional time and resources are accounted for dismantling the track. The hourly requirements of the machinery and plant were then multiplied by their equivalent EF, which was based on the type (diesel, petrol – two/four stroke) and (engine) size (in kW/hp) as sourced by RSSB (2018). This calculation has been made indirectly using the equation 5.4 shown below.

$$EC^{s}_{Pj} = \sum_{j,i=1}^{n} DT_j \times CF_{ji} \tag{5.4}$$

Where, EC^{s}_{Pj} is the CO_2e emissions arising from the use of machinery and equipment for the construction and relay/renewal on site in kg of CO_2e per FU selected; j is the machinery index; $i = 1, 2, 3, \ldots, n$ corresponding to a rated power of $4kW, \ldots, n$; n is the total number of machinery and plant used in the installation/renewal of each design; DT_j is the operating time for machine j given in $hours$; CF_{ji} is the CF for machine j with engine size i given in $kgCO_2e/hour$ of combustion.

For installation and renewal processes, the machinery and plant is assumed to be delivered on site using low loaders. The average journey time for a single low loader delivering plant is around 2.5 hours (5 hours for the round trip) (RSSB, 2018). Thus, based on the total quantity of plant necessary in each case, the number of low loaders needed has been multiplied by the average journey time per low loader to calculate the total travel time. This was then used to calculate the transport emissions for machinery and plant by multiplying the total travel time by the CF for a low loader (Diesel Engine - 70 kW/94.5 hp) given in $kgCO_2e/hour$ of combustion. In a similar manner, rail-mounted machinery (e.g. tampers, locomotives, etc.) required during the installation/renewal procedures have been assumed to have identical average journey times as above, however, they were assumed to be self-propelled on site instead of being delivered using low loaders.

TABLE 5.3: Example of input data (for machinery and plant) for the complete renewal (incl. dismantling) of an NR60 FV 1 in 21 Turnout. Sources: RSSB (2018)

Category	Work description	Operation (hours)	Notes	Engine type and size	CF ($kgCO_2e/hour$)
Road Rail Vehicles (RRVs)	Lift out panels	6	Scrap out 2 × RRVs 3 hours	Diesel Engine - 70 kW/94.5 hp	57.520
	Excavation	6	2 × RRVs 3 hours	Diesel Engine - 70 kW/94.5 hp	57.520
	Bottom ballast	4	2 × RRVs 2 hours	Diesel Engine - 70 kW/94.5 hp	57.520
	Relay sleepers/bearers	5.5	Assume Kirow Crane (4 × S&C + 3 × PL)	Diesel Engine - 70 kW/94.5 hp	57.520
	Install rail, clip up, clamp	0	n/a	Diesel Engine - 70 kW/94.5 hp	57.520
	Boxing ballast	0	n/a	Diesel Engine - 70 kW/94.5 hp	57.520
	Travel to and from the site	15		Diesel Engine - 70 kW/94.5 hp	57.520
Tampers	Convey into position	1	1 × S&C Tamper	Locomotive - 450 kW/607.5hp	358.600
	First run	2.5		Locomotive - 450 kW/607.5hp	358.600
	Second run	1.5		Locomotive - 450 kW/607.5hp	358.600
	Travel to and from the site	5		Locomotive - 450 kW/607.5hp	358.600
Dozers	Excavation	3		Diesel Engine - 100 kW/135 hp	80.590
	Bottom ballast	2		Diesel Engine - 100 kW/135 hp	80.590
Locomotives	Idling on site	54		Locomotive - 2000 kW/2700 hp	1594.000
	Transitting from site to depot	16		Locomotive - 2000 kW/2700 hp	1594.000
Small Plant	Diesel Generators (mobilising site)	108		Diesel Engine - 4 kW/5.4 hp	3.413
	VIB-01 Concrete Vibrator 8kW	0		Petrol Engine - 4 Stroke - 8 kW / 10.8 hp	12.150
	Fast Clip Machine	0		Diesel Engine - 4 kW/5.4 hp	3.413
	Triple Whacker Plate	1.5		Diesel Engine - 15 kW/20.25 hp	12.800
	Impact Wrench	2.5		Diesel Engine - 4 kW/5.4 hp	3.413

5.2.4.3 Component Transport Emissions

The CFs drawn from the RSSB's Rail Carbon Tool and Bath Inventory of Carbon and Energy (Hammond and Jones, 2011, 2019) are quoted as 'cradle-to-gate' rather than 'cradle-to-site' boundaries, hence, an arbitrary transport distance of 100 km has been chosen for all components, with the subsequent direct emissions assumed to arise either via low loader trucks or freight trains, with the components assumed to be pre-assembled in the factory (in panels). Consequently, in order to evaluate the direct embodied emissions arising from the transportation of these components, the DBEIS Heavy Goods Vehicle (HGV) 'all diesel' and the rail freight 'all scope' EFs (DBEIS, 2021) quoted in $kgCO_2e/kg$ or $tonne\ km$ has been used (using equation 5.5).

$$EC_{T-R_j} = \sum_j \sum_i (M_{ji} \times T_{ji} \times CF_i) \tag{5.5}$$

Where, EC_{T-R_j} is the direct carbon emissions arising from the transportation of material, equipment and waste j expressed in kg of CO_2e per FU selected for track refurbishment, repair and renewal activities; M_{ji} is the amount of building material, component, equipment or waste j (in kg) to be transported by vehicle i; T_{ji} is the total transport distance for item j transported via vehicle i (in km); CF_i is the EF to transport an item using vehicle i (in $kgCO_2e/tonne \times km$). In this case the EF is assumed to be for a vehicle, which is 100% laden.

For the initial track construction, equation 5.5 has been reworked to reflect that on the return trips the vehicles will be 0% laden (see equation 5.6).

$$EC_{T-C_j} = \sum_j \sum_i (M_{ji} \times T^a_{ji} \times CF^a_i + T^b_i \times CF^b_i) \tag{5.6}$$

Where, EC_{T-C_j} is the direct carbon emissions arising from the transportation of material, equipment j expressed in kg of CO_2e per FU selected for track construction activities; M_{ji} is the amount of building material, component, equipment j (in kg) to be transported by vehicle i; T^a_{ji} is the total 'gate to site' transport distance for item j transported via vehicle i (in km); CF^a_i is the EF to transport an item using vehicle i (in $kgCO_2e/tonne \times km$), assuming the vehicle is 100% laden; T^b_i is the total 'site to gate' transport distance for vehicle i (in km); CF^b_i is the EF for the return trip of vehicle i to the factory/depot (in $kgCO_2e/km$), assuming that it is 0% laden.

5.2.4.4 Labour Emissions

Considering emissions from labour, two different scenarios have been adopted: (i) Business as Usual (BAU) and (ii) Covid – 19 pandemic scenario. The former differentiated from the latter by permitting car sharing (two passengers per vehicle) for labour and hotel stays (in case track possession time is scheduled to be longer than a standard eight hour shift). For the latter scenario, an alternative has been also examined, assuming that labour travels on site by National rail instead of using petrol vehicles, in order to reflect the partial relaxation of Covid – 19 lockdowns.

It was assumed that turnout/crossover sites average around 10 × shifts per hour, throughout the duration of a standard possession (RSSB, 2018). Labour was assumed to travel on site by petrol car, assuming an average distance travelled of approximately 96 km (192 km for the round trip), which was based on the average travel time to site for a core job being 1 hour and 15 minutes (RSSB, 2018). Possessions times were derived based on the scheduled hours of operation (see for example, Table 5.3) for each work activity (construction, renewals, repair, refurbishment) and scaled for each design variant depending on the number of panels to be installed, repaired or renewed in each case. Summarising, the emissions from labour travel have been calculated using the equation 5.7.

$$EC_{T-Lij} = P_{ij} \times L \times D \times CF \tag{5.7}$$

Where, EC_{T-Lij} is the direct carbon emissions arising from the transportation of labour to and from the site for design variant i and work activity j, expressed in kg of CO_2e per FU; P_{ij} is the site possession time for design variant i and work activity j, expressed in *hours*; L is the labour per hour of standard site possession, set by default as 10 (for the car sharing option, this number is divided by two to reflect a vehicle passenger occupancy rate of two passengers). D is the (to and from the site) transport distance for labour, set as 192 km; CF is the EF for labour travelling to and from the site (in $kgCO_2e/km$), assuming travel either by petrol car ('Car - Average - Petrol') or by National rail services ('Rail - National Rail') based on the EFs by DBEIS (2021).

For the BAU scenario, where hotel stays were included, these emissions were calculated based on the number of night stays and rooms booked. The number of night stays for each work activity was derived based on the total scheduled time for possession, which was divided by eight to reflect standard eight hour shifts for labour. Furthermore, all rooms have been assumed as two bedroom for simplicity. Finally, for each case the derived night stays have been multiplied by the number of rooms and the EF for hotel stays (given in $kgCO_2e$ per room per night) for the UK by DBEIS (2021).

5.2.4.5 Track Maintenance and Renewal Emissions

In terms of maintenance, two different standard options have been examined for S&Cs: tamping and rail grinding. Fuel consumption data for both machines have been sourced in *litres* per *metre* by Kaewunruen and Lian (2019) as shown in Table 5.4.

TABLE 5.4: Maintenance machinery input data.
Sources: Kaewunruen and Lian (2019); DBEIS (2021)

Plant	Fuel Type	Fuel Consumption	CF
		$litres/metre$	$kgCO_2e/litre$
S&C tamping machine	Diesel	0.300	2.512
S&C grinding machine	Diesel	0.300	2.512

The maintenance emissions for each design variant and work activity have been calculated using equation 5.8 shown below.

$$EC^{s}_{Mij} = C_j \times L_{ij} \times CF_d + JT_j \times CF_j \tag{5.8}$$

Where, EC^{s}_{Mij} is the CO_2e emissions arising from the transport (to and from the site) and use of maintenance machinery and equipment j for maintaining design variant i in kg of CO_2e per FU selected; C_j is the fuel consumption of machinery or equipment j given in $litres/metre$; L_{ij} is the length of ballasted track to be processed (given in single track metres) by machine j for maintaining design variant i - for the case of tamping, it was assumed that tampers work in pairs (parallel tamping to ensure even consolidation) and perform two passes each, in accordance with NR practices [1]; CF_d is the CF for diesel, given in $kgCO_2e/litre$ of fuel burnt from combustion; JT_j is the average journey time (to and from the site) for machine j, given in $hours$ (taken as 5 hours); CF_j is the CF for machine j given in $kgCO_2e/hour$ of combustion.

Considering track renewal activities, four different options have been considered: complete renewal, ballast, sleeper/bearer and rail renewal. The first option assumes that the entire track is being replaced as whole. Ballast renewal assumes excavation of the track, and replacement of the ballast and sub-ballast layers, followed by two tamping passes. For sleeper renewals, both sleepers and bearers are being replaced, including miscellaneous components attached underneath them (e.g. USP). Whereas, for rail renewals, it was assumed that rails, check rails and the remaining miscellaneous components are being renewed (fastening, baseplates, insulators, pads, fishplates, joints, screws, washers, etc.). The carbon footprint calculations for each of these activities are made following the methodology discussed in sections 5.2.4.1 to 5.2.4.4.

TABLE 5.5: Pilot sites for NR 60 Mark 2.
Sources: Bostock (2021)

Site	Year	Layout	Notes
Thirsk	2017	C 13 crossover	High speed route
		D 15 crossover	
Ulceby	2019	C 13 crossover	Heavy freight route
		D 10.75 turnout	
		E 15 turnout	
Farnborough	2019	E 21 crossover	3rd rail electrification
		C 13 crossover	
Cogload	2019	C 13 crossover	
Cricklewood	2020	G 28 crossover	First Hy-drive layout
Balham and Falcom junction	2021	Double junction	First NR 60 Mark 2 double junction and three line crossover

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[1] Winship, P., 2022. Personal communication (Network Rail)

In order to evaluate the long-term performance of the targeted S&Cs, information on the maintenance demands and service lives is required as input. However, such data was not readily available for each design variant, therefore, this analysis adopted average values given by Kaewunruen and Lian (2019). The primary reason for these limitations is that such data records were not made available, but also from the fact that the Mark 2 designs are relatively new, counting a small number of installations on the network and limited number of operational years (see Table 5.5).

TABLE 5.6: Maintenance and renewal cycles adopted in this study.
Sources: Kaewunruen and Lian (2019)

Design Variant	Work Activity	Service Life (Scenario)			
		M	*A*	*B*	*C*
NR 56 V	Rail grinding	2 years	=	=	=
	Ballast tamping	4 years	=	=	=
	Ballast replacement	20 years	=	=	=
	Bearers/sleeper renewal	30 years	=	=	=
	Rail renewal	10 years	=	=	=
	Renewal (Complete)	60 years	=	=	=
NR 60 Mark 1	Rail grinding	2 years	4 years	=	4 years
	Ballast tamping	4 years	=	8 years	8 years
	Ballast replacement	20 years	=	40 years	40 years
	Bearers/sleeper renewal	30 years	=	=	=
	Rail renewal	10 years	20 years	=	20 years
	Renewal (Complete)	60 years	=	=	=
NR 60 Mark 2	Rail grinding	2 years	4 years	=	4 years
	Ballast tamping	4 years	=	8 years	8 years
	Ballast replacement	20 years	=	40 years	40 years
	Bearers/sleeper renewal	30 years	=	=	=
	Rail renewal	10 years	20 years	=	20 years
	Renewal (Complete)	60 years	=	=	=

(=) Denotes that service life is identical to that of Scenario *M*.

Considering the above, the main scenario in this chapter, maintains identical service lives across all design variants. However, to reflect some of the potential benefits of the Mark 1 and Mark 2 design variants (see section 5.2.2), three additional scenarios (see Table 5.6) have been introduced were the maintenance and renewal intervals are being halved for: (1) rails and miscellaneous components, (2) ballast, and a (3) combination of these components.

5.2.4.6 End-of-Life

Considering the EoL stage of the analysis, as data was not readily available on the exact pathway of each component, a number of assumptions had to be made. First, it was assumed that 90% of the aggregate is recycled, with 10% being disposed to landfill, in accordance with BRE Global Ltd (2016). Furthermore, based on BRE Global Ltd (2016), it was assumed that the ballast recovered through recycling is used as secondary aggregate (replacing virgin crushed rock) or fill material for a number of construction applications, including road building and landscaping.

For rail sections, it was assumed that 1% of steel is disposed to landfill, with 92% of steel being recycled and the remaining 7% being reused (British Steel Ltd, 2020). Whereas, for steel miscellaneous components (e.g. fastening, baseplates, etc.), a use of 85% recycled steel was assumed. Conversely, the rebar used for reinforcing concrete sleepers and bearers was assumed to be made from 100% virgin steel.

Allocation

According to ISO (2006b), when it comes to reuse of recycling, there is a standard distinction between allocation procedures: (1) Open and (2) Closed loop. The former is used to describe a material that is either recycled into a new different product or its inherent properties change. Whereas the latter applies to a material, which is recycled into the same product or where its inherent properties remain the same.

Methodologies : Recycling or reuse

Presently, there are many different methodologies for modelling recycling. To avoid confusion on the interpretation of results at later sections, the three main approaches (targeting specifically carbon footprinting) are going to be discussed briefly here.

Generally, there are three key approaches underpinning most known methods, these are the:

1. Recycled content method (100 – 0)
2. Substitution method (0 – 100)
3. 50/50 method (50 – 50)

For the ′recycled content′ method (also known as ′cut-off′ approach) the impacts of producing a virgin material are attributed at their entirety at the product in which this is first used. On the contrary, any impacts related to recycling are allocated to those products providing the recycling materials (Allacker et al., 2014). Modelling and reporting under this method, incentivises increases on the % of recycled materials used in a product, as any potential benefits or burdens are only accounted on the input side, whereas recycling at the EoL is neglected regardless (of the rate).

For the ’substitution’ method (also known as recyclability or EoL approach) it is assumed that the properties of the original material input are retained by the produced recycled materials at the EoL, however, in this case, these are credited with an avoided burden based on the reduced requirements for virgin resource production in the next life cycle (Allacker et al., 2014). It is worth noting, that the actual recycled content in the primary product is not accounted for (Allacker et al., 2014). Therefore, modelling and reporting under this method, incentivises a focus on recycling at the EoL.

Finally, the ’50/50’ method is often described as a ’compromise’ approach between the two aforementioned methodologies as the burdens from recycling are credited in equal proportions between both the starting and subsequent product (Allacker et al., 2014).

For an in-depth overview of allocation and recycling methods, including detailed formulations and worked examples, the reader should review the work by Allacker et al. (2014, 2017).

In this chapter, EoL results (for railway ballast and steel components) are presented using both the ’recycled content’ (100-0) and ’substitution’ (0-100) methods. For transparency, the main results will be presented under the (100-0) approach, whereas, any subsequent benefits or burdens beyond the examined boundaries of this study will be presented separately (see section 5.2.4.7) in accordance with the guidance by BSI (2016).

5.2.4.7 Benefits and Burdens beyond the System Boundary

According to BSI (2016), this phase should include the “avoided carbon emissions associated with the infrastructure asset including potential for re-use, recovery and recycling of materials and/or energy and associated carbon emissions beyond the system boundary”. It is also stated that this stage “might also be used to record benefits or loads arising from additional functions of infrastructure” (BSI, 2016).

In this chapter, the benefits and burdens (from recycling and recyclability) of steel are calculated based on tool developed by Hammond and Jones (2019), which is underpinned by the data and methodology by the World Steel Association (2017). The base formula for this model (equation 5.9) is shown below:

$$EC_{steel} = X - (RR - S) \times Y \times (X_{pr} - X_{re}) \tag{5.9}$$

Where, EC_{steel} is the EC for 1 kg of steel product, including recycling; X is the cradle-to-gate, EC of steel; $(RR - S)$ is the amount of net scrap produced from the system; RR is the EoL recycling rate of the steel product; S is the scrap input to the steel making process; $Y \times (X_{pr} - X_{re}$ is the LCI value of steel scrap; Y is the process yield of the of the Electric Arc Furnace (EAF); X_{pr} is the EC for 100% primary production of metal - theoretical value for steel made in the Basic Oxygen Furnace (BOF) by assuming no scrap input; X_{re} is the EC for 100% secondary production of metal - theoretical value for steel made in the EAF by asssuming 100% scrap input.

Considering railway ballast and sub-ballast, the equivalent benefits and burdens from EoL practices were based on the data presented by BRE Global Ltd (2016).

5.3 Results and Discussion

5.3.1 Simulated Scenarios

In total 12 programmed scenarios (for 15 different S&Cs) have been tested (Table 5.7). These scenarios differentiate in terms of: (i) track performance, measured by the amount of interventions needed throughout a 60-year life cycle, (ii) Pre/Post Covid – 19 travel conditions for labour, (iii) transport options (road or rail) for materials, machinery and plant.

A total of 180 scenario combinations have been tested, examining in detail the carbon footprint of different variants of turnouts and crossovers used in the UK. Each of these scenarios is presented in Table 5.7.

5.3.2 LCA Modelling Results

5.3.2.1 Carbon Footprint Results : Cradle-to-Site

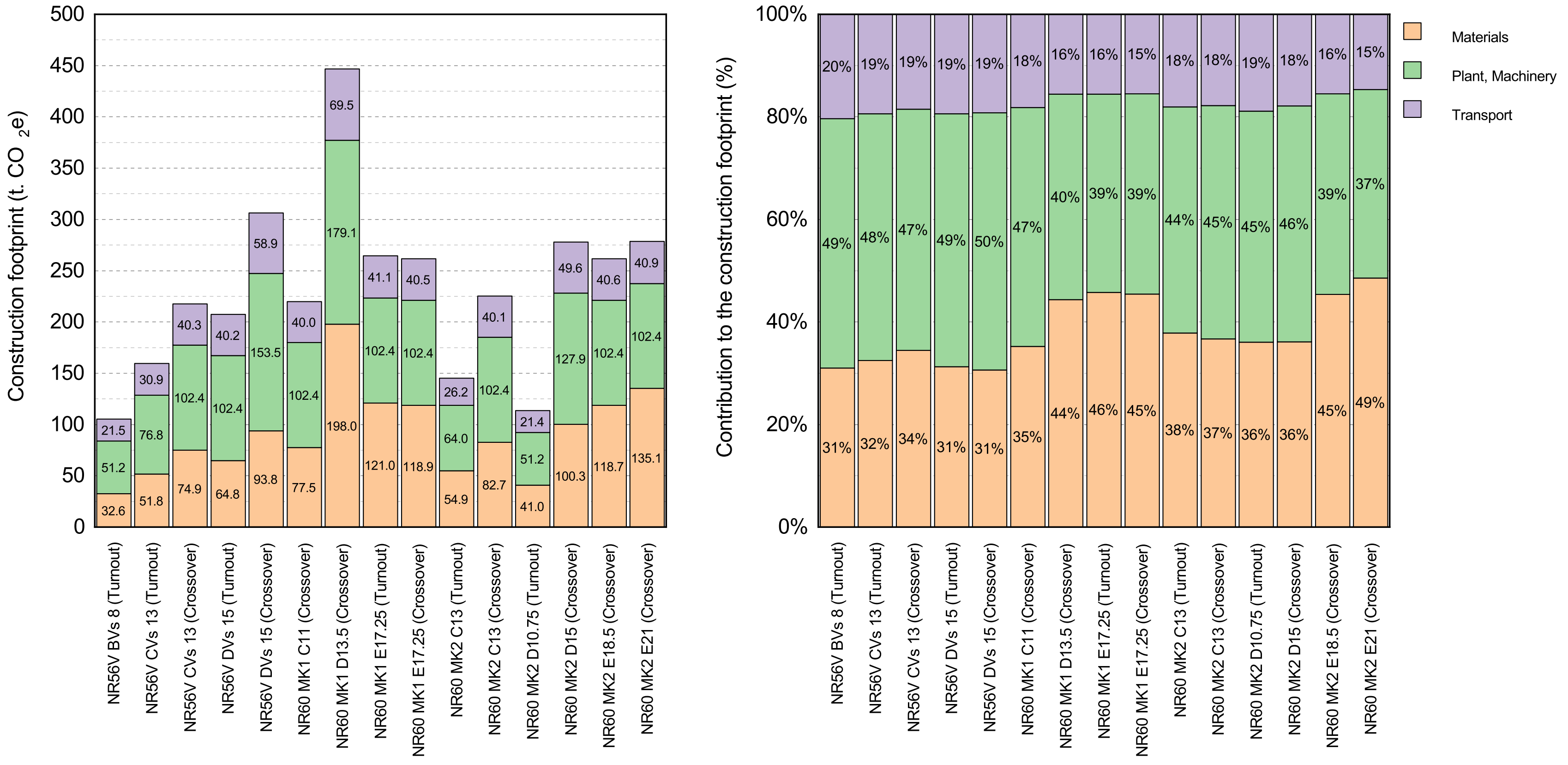
The carbon footprint associated with the construction phase (cradle-to-site) of the S&Cs is common across each group of scenarios (M - C, M_1 - C_1, M_2 - C_2). Similarly, to the previous chapter, these emissions are split into three primary areas: (i) EC emissions associated with the materials/components used, (ii) direct emissions associated with the transportation of materials, labour, machinery and plant to and from the construction site, and (iii) the emissions originating from the machinery and plant during the track construction process.

Considering the first group (M - C) of scenarios (see Figure 5.4), it has been found that on average plant and machinery have the largest share of emissions to the total construction footprint of around 44.29% (c. 51.2 to 179.1 $t.CO_2e$ in absolute terms). The impact of material and components was found (on average) to be the second highest, with a contribution of about 38.07% (c. 32.6 to 198.0 $t.CO_2e$ in absolute terms, depending on the design variant examined). Whereas, the transport of plant, labour and materials had the least impact, accounting on average for just about 17.64% (c. 21.4 to 69.5 $t.CO_2e$ in absolute terms). The overall footprint of construction phase (Figure 5.4) for this group of scenarios was found to be significant, ranging between 105.3 to 446.6 $t.CO_2e$, depending on the design variant examined.

For the second group (M_1 - C_1) of scenarios, the ranking of contributing parameters was found to be the same. However, there was a minor reduction on the average % contribution of plant and machinery (43.04%) and materials (37.02%). Conversely, the impact of transport increased in absolute terms, ranging between 24.8 to 81.2 $t.CO_2e$ depending on design variant examined, this resulted to the average contribution of this phase to increase by 2.3% (c. 19.93%). These increases on the transport footprint during track construction, resulted to a higher total construction footprint, ranging between 108.6 to 458.2 $t.CO_2e$. These increases in the overall impact of transport stem from the fact that in this group of scenarios, car sharing was restricted (Pandemic scenario) and every member of staff had to travel to and from the site using his/her own petrol vehicle.

TABLE 5.7: Overview of simulated scenarios.

No.	Label	Design variant	Performance	Pre/Post Covid-19	Transport
1	M	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Identical service life across variants	Hotel stay and car sharing	Road
2	A	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for rail and miscellaneous components	Hotel stay and car sharing	Road
3	B	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for railway ballast	Hotel stay and car sharing	Road
4	C	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for rail, ballast and miscellaneous	Hotel stay and car sharing	Road
5	M_1	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Identical service life across variants	No hotel sharing or car sharing	Road
6	A_1	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for rail and miscellaneous components	No hotel sharing or car sharing	Road
7	B_1	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for railway ballast	No hotel sharing or car sharing	Road
8	C_1	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark1 and Mark 2 designs offer higher service life for rail, ballast and miscellaneous	No hotel sharing or car sharing	Road
9	M_2	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Identical service life across variants	No hotel stay	Rail
10	A_2	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for rail and miscellaneous components	No hotel stay	Rail
11	B_2	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for railway ballast	No hotel stay	Rail
12	C_2	(5) NR56, (4) NR60 Mark 1, (6) NR60 Mark 2	Mark 1 and Mark 2 designs offer higher service life for rail, ballast and miscellaneous	No hotel stay	Rail



(A)

(B)

FIGURE 5.4: (A): Carbon footprint of construction (materials, transport, labour and plant) in tonnes of CO_2e and (B): Percentage contribution of each item to the construction footprint per design variant for Scenarios: M, A, B, C.

Considering now the final group (M_2 - C_2) of scenarios, it has been observed that as above, the ranking of contributing parameters to the construction footprint remained identical. The average impact of plant and machinery had again the largest share of about 45.4% (c. 51.2 to 179.1 $t.CO_2e$). Similarly, the impact of materials and components was found to account for around 39.0% (c. 32.6 to 198.0 $t.CO_2e$). Whereas, the impact of transport exhibited a considerable decrease, ranging between 18.6 to 58.9 $t.CO_2e$ in absolute terms, depending on the design variants examined. The average contribution on transport during the construction phase was found to be at around 15.5%. This result is not surprising considering that under these scenarios (M_2 - C_2), transport of materials, labour, machinery and plant was made exclusively (if possible) by rail, and overnight hotel stays were restricted. These assumptions resulted to the average footprint of construction to range between 102.4 to 436.0 $t.CO_2e$.

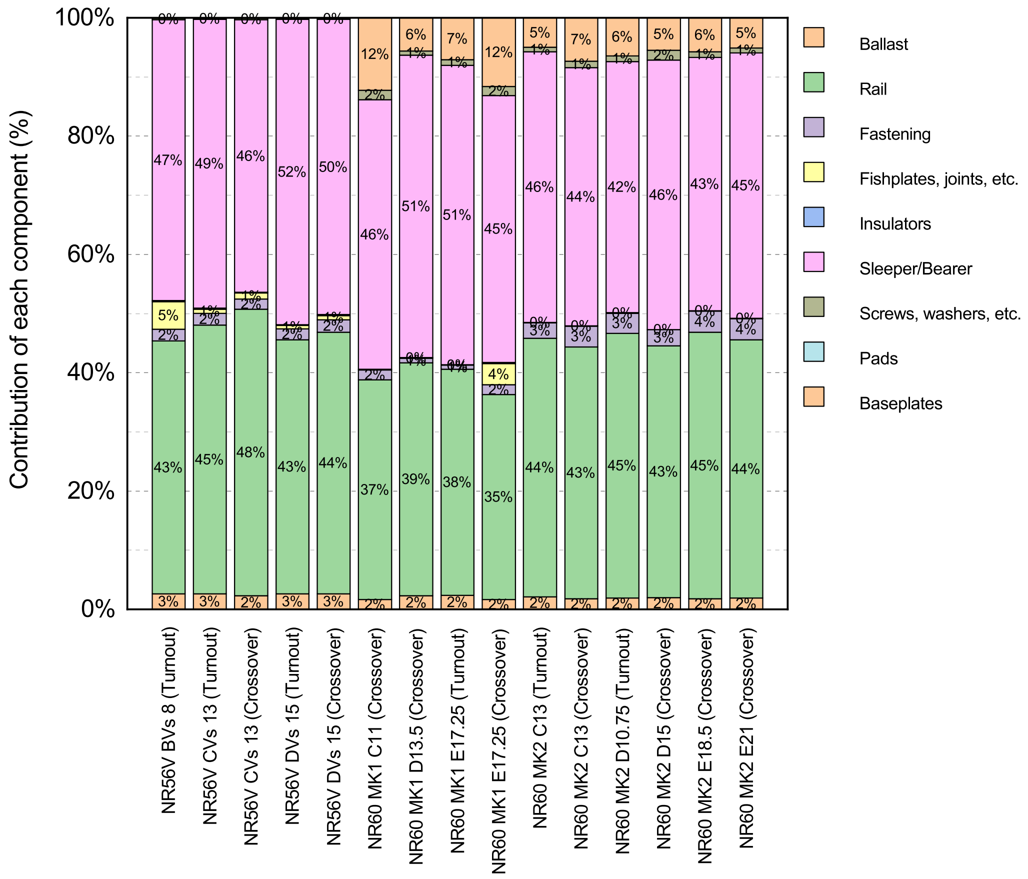


FIGURE 5.5: Contribution (%) of each component to the embodied emissions of the construction footprint.

When comparing the overall impact of construction for crossovers, this was found to be around 36.5% to 55.2% higher to that of their equivalent turnout. However, such comparisons were not always possible to be made for all designs due to data unavailability, and in one case the construction footprint of a turnout was found to be marginally higher than that of its equivalent crossover. This could be explained from the fact that the data for these designs were based on actual installations and perhaps for this specific project, a higher number of plain track panels had to be renewed, resulting to a higher overall impact on its construction footprint. In an attempt to resolve this issue, the carbon impact of construction for each design has been normalised by its equivalent length. It has been found that the overall impact of construction for crossovers compared to their equivalent turnouts (in terms of design specification, switch size and crossing angle) is higher by about 24.8% to 46.8%.

Examining the contribution (%) of each component to the embodied emissions (see Figure 5.5) of construction materials, it had been found that on average sleepers/bearers, followed by rails (incl. switch, crossing, etc.) have the largest share on these emissions. In detail, taking as an example the results of scenarios '*M* - *C*' (see Figure 5.5), the embodied emissions of sleepers and bearers account on average for about 46.8%, with rails being next on the list, having a contribution of 42.4%. Similarly, baseplates have a considerable share on these emissions (c. 7.2%), whereas, ballast and the fastening system have nearly identical average share of emissions of about 2.2%. The remaining components have a negligible contribution (below 1%) to these emissions. These results are not surprising, as both sleepers and bearers, as well as rails, make extensive use of steel and concrete, which are highly carbon intensive materials.

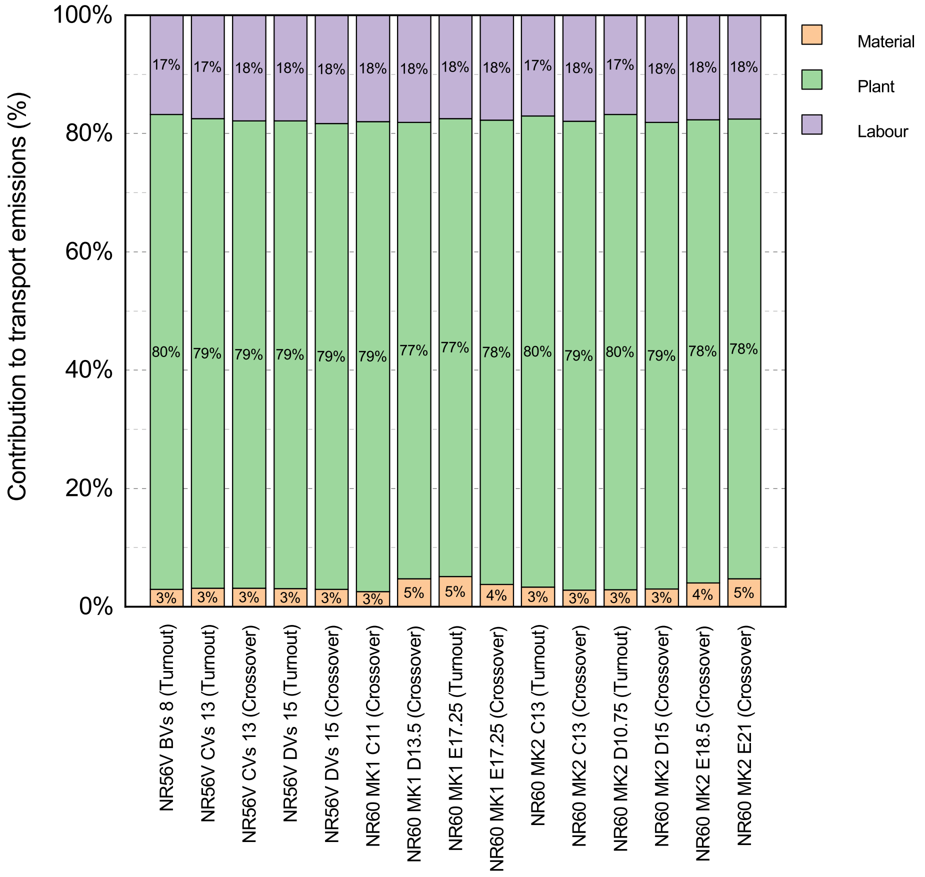
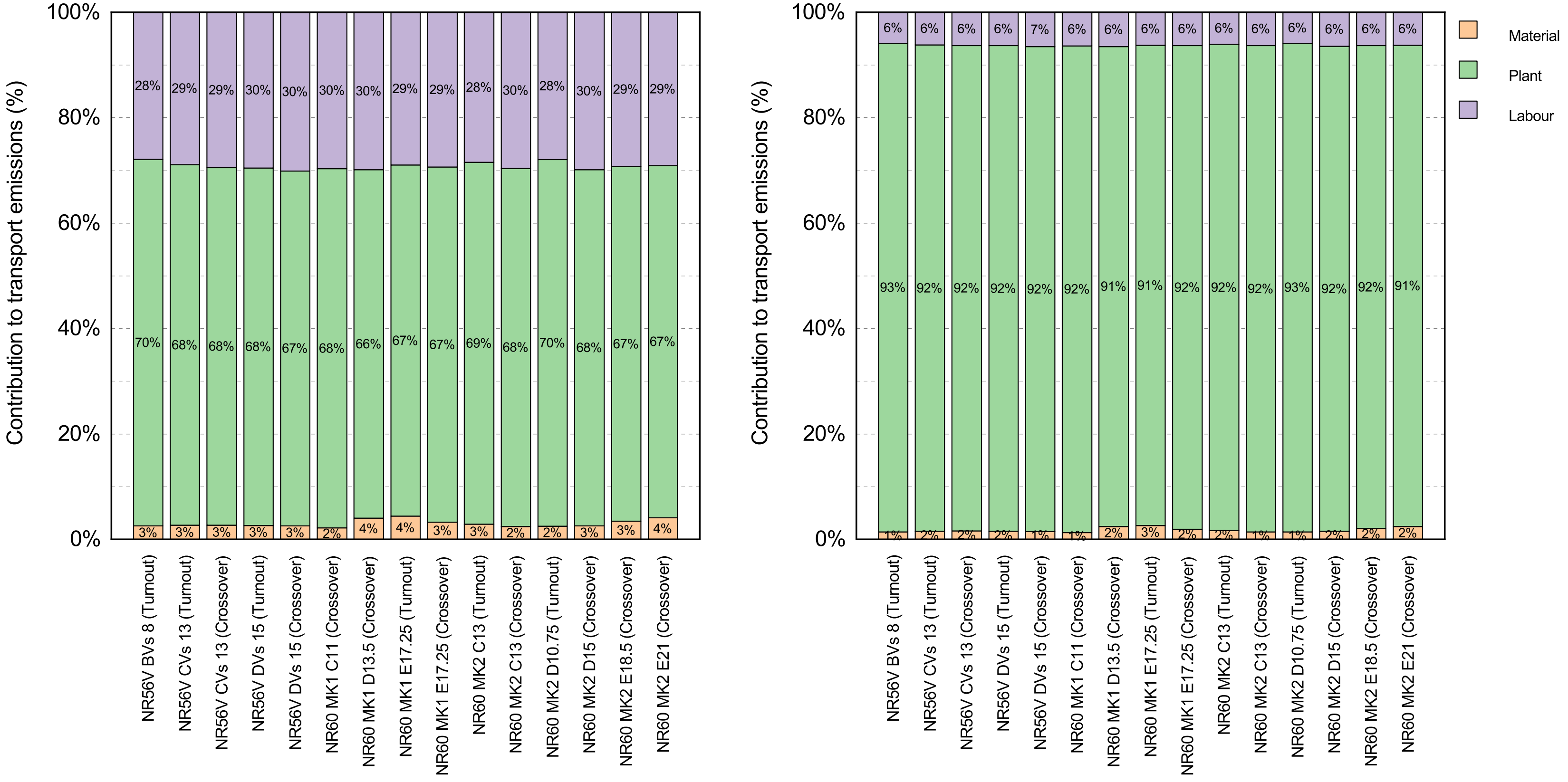


FIGURE 5.6: Contribution (%) of each transport category to the transport emissions of the construction footprint.

Transport emissions during track construction (see Figure 5.6) were also considerable, with the transportation of machinery and plant (to and from the site) making the most of these emissions, accounting on average for about 78.9%. This was followed by the transport of labour, which accounted on average for around 17.7%, while the transportation of materials and components had the least contribution, accounting for just about 3.5%.



(A) M_1 - C_1

(B) M_2 - C_2

FIGURE 5.7: Contribution (%) of each transport category to the transport emissions of the construction footprint.

Looking at the breakdown of transport emissions (during track construction) for the second set of scenarios (Figure 5.7a), it was found that the average share of machinery and plant is now reduced to 67.8% (from 78.9%). Similarly, the share of the transportation of materials and components was reduced to 3.0% (from 3.5%). Conversely, the impact of labour transport has now increased from 17.7% to 29.2%. This is a result of the assumption (for this set of scenarios) of restricting car sharing for labour, when travelling to and from the construction site.

For the final set of scenarios, the breakdown of transport emissions during the construction process is changed significantly (Figure 5.7b). In detail, the transport share of materials and labour is now around 1.7% and 6.3%, respectively. These reductions are of course linked to the modal shift from road to rail for materials and labour.

Finally, irrespectively of the scenario examined, the breakdown of machinery and plant emissions during track construction is dominated by the emissions from the use of locomotives (c. 96.1%), followed by those from tampers, RRVs, dozers and small plant, accounting for the remaining 3.9% of the operating emissions from plant use.

5.3.2.2 Carbon Footprint Results : Cradle-to-Grave

Scenario : Business-as-Usual

The first group of scenarios assumed that the transport of materials and labour to and from the site is made by road. Each of the individual scenarios (*M* to *C*) examine alternative options with respect to maintenance and renewal intervention cycles for different components (Table 5.6). Starting from scenario *M* (which assumes that all designs have identical maintenance and renewal cycles), focusing first on turnouts (Figure 5.8), it is found that the higher the crossing angle of an S&C, the higher is its total footprint. When comparing equivalent turnouts, the only feasible comparison can be made between the NR 56 v C13 and the NR60 Mark 2 C13, as they both have identical switch size and crossing angle. Based on the analysis, it is found that the Mark 2 design performed marginally better than the equivalent NR56 design variant, by emitting c. 3.5% less GHG emissions over a 60-year period. Considering railway crossovers (Figure 5.8), as with turnouts, parameters such as crossing angle and switch size remain relevant as control factor for the total carbon footprint of an S&C. Generally, higher crossing angles and switch sizes, resulted to a higher total footprint. However, there were some cases, that designs with smaller switch size and crossing angle, had a higher total footprint (e.g. NR60 Mark 1 D13.5). It is likely that for certain designs, more materials/components were necessary for particular sites, and as the data inputs were based on specific UK installations, this may have led to inconsistent results. When comparing equivalent crossovers, it is found that the NR56 v C13 variant performs marginally better than the NR60 Mark 1 crossover, by emitting 4.9% less GHG emissions. Conversely, the NR56 v D15 design was found to have a higher total footprint (c. 4%) than the NR60 Mark 1 D15 crossover. Summarising, when comparing crossovers against their equivalent turnouts, it is concluded that on average, crossovers have a higher carbon footprint by about 25 to 31%.

Looking at the breakdown of the overall carbon footprint by LCA phase (see Figure 5.9), it can be inferred that for scenario M, the impact of S&C renewals is the greatest, accounting on average for about 61.3% of the total footprint. The biggest contributor to this figure is complete

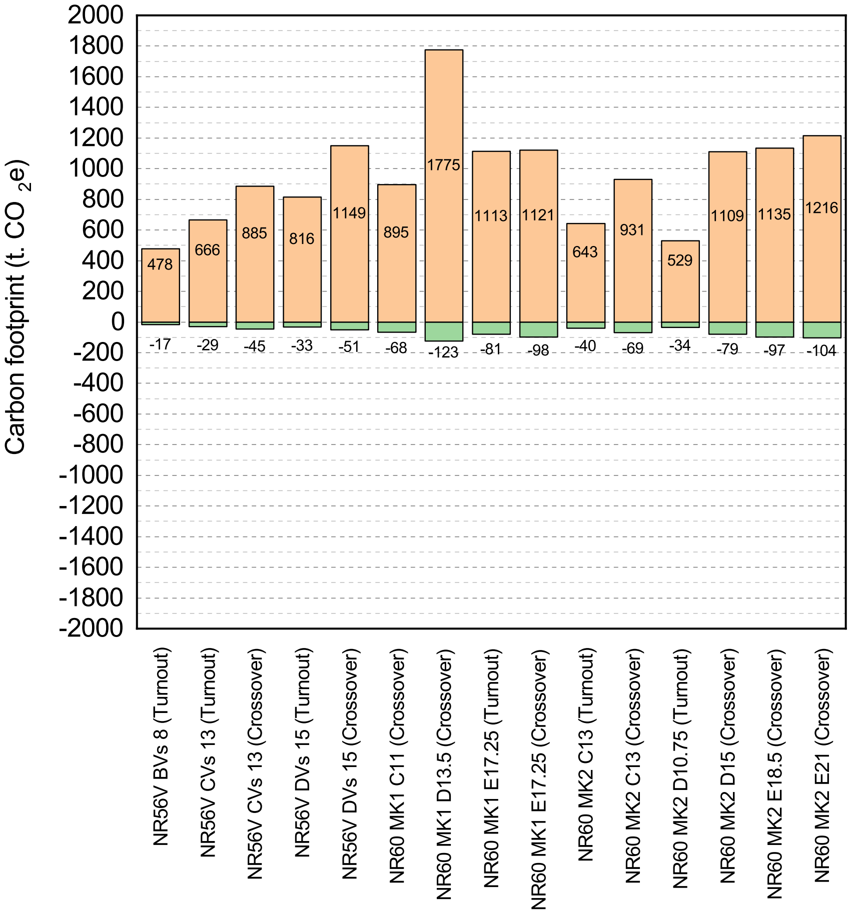


FIGURE 5.8: Carbon footprint for 60-year lifecycle. Scenario: *M*.

renewals (27.4%), followed by rail renewals (25.8%). Whereas, ballast and sleeper/bearer renewals account for less than 5% of the footprint. Construction of the infrastructure is also responsible for a sizeable share of the total GHG emissions, having an average contribution of 23.9% (c. 105 to 447 $t.CO_2e$). Maintenance actions had also a sizeable contribution to the total footprint (13.6%) by emitting on average between 89 to 101 $t.CO_2e$ (for rail grinding) and 23 to 28 $t.CO_2e$ (for S&C tamping). Finally, the EoL phase was found to have the least average contribution to the total footprint of about 1.2% (c. 5 to 28 $t.CO_2e$ in absolute terms).

In scenario *A*, the same assumptions apply (with respect to transport of materials and labour) as in scenario *M*. The only difference between the two scenarios is the assumption that for the NR60 Mark 1 and Mark 2, the maintenance and renewal cycles for the rails (incl. switch, miscellaneous components) and crossing are double that of the NR56 v variants. This scenario was selected to reflect the benefits from the improved performance of the super-structure by the introduction of these designs (see section 5.2.2). Comparing our results between the two scenarios, it was found that the total footprint of the Mark 1 and Mark 2 designs was reduced on average by about 21.6% (22.0% for turnouts and 21.5% for crossovers). Looking now at equivalent turnout designs, the NR60 Mark 2 C13 displayed a significant improvement on its environmental impact, compared to the equivalent NR56 v turnout, by emitting c. 24.6% less GHG emissions over a 60-year period.

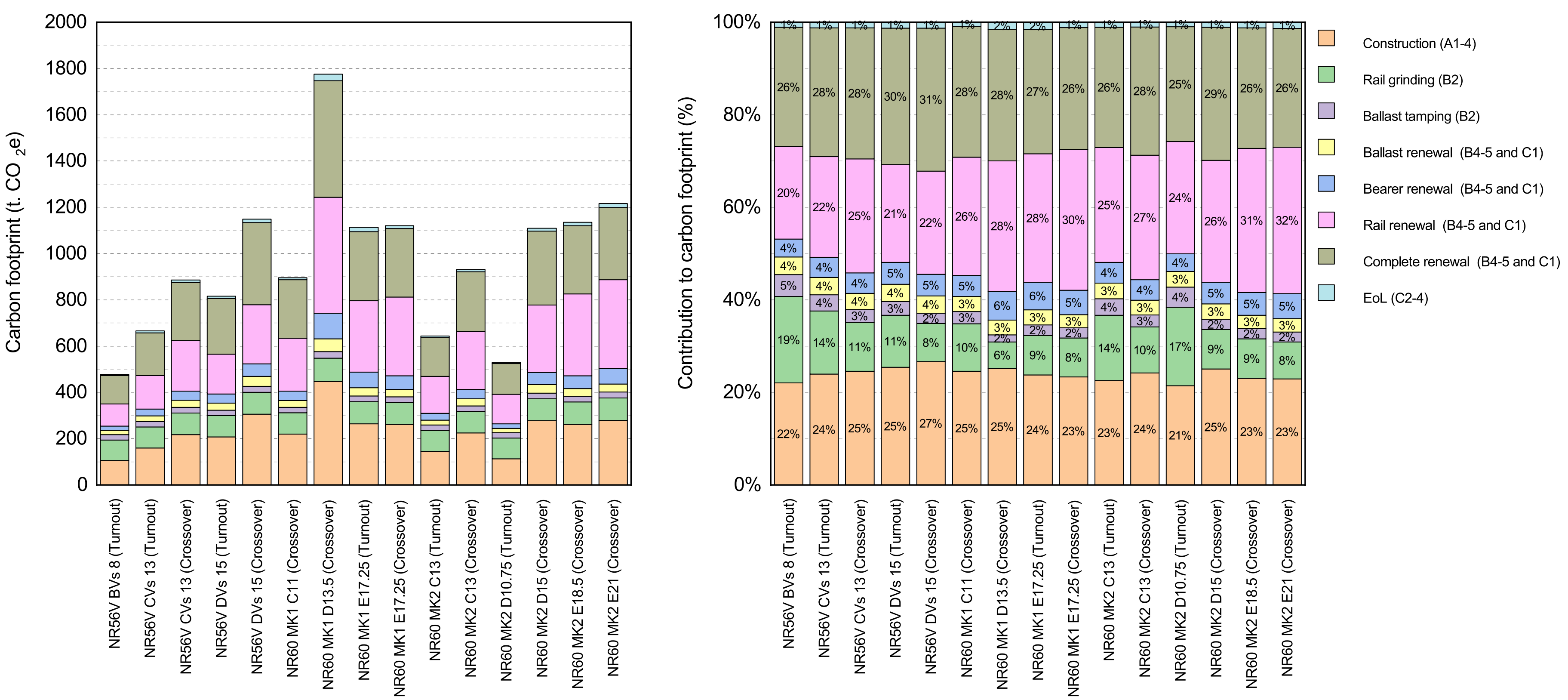


FIGURE 5.9: Carbon footprint per lifecycle stage. Scenario: *M*.

Comparing now the equivalent crossovers, it is found that both NR60 Mark 2 designs (NR60 Mark 2 C13 and D15) have a lower total footprint (17.1% and 22.9%) than their equivalent NR56 variants (Figure 5.10). Looking at the breakdown of the total carbon footprint by LCA phase (see Figure 5.11), the impact of S&C renewal remains the highest, accounting for about 58.7% (61.3% for scenario *M*). This is a direct implication of our assumption of effectively doubling the service life and halving the maintenance cycle for steel components, reducing the average impact of maintenance and renewal of these components by 45 to 51 $t.CO_2e$ and 77 to 300 $t.CO_2e$, respectively. Construction of the infrastructure remains a major contributor to the total footprint by accounting on average for about 28.2%. The EoL phase once again has the least average contribution of around 1.4%.

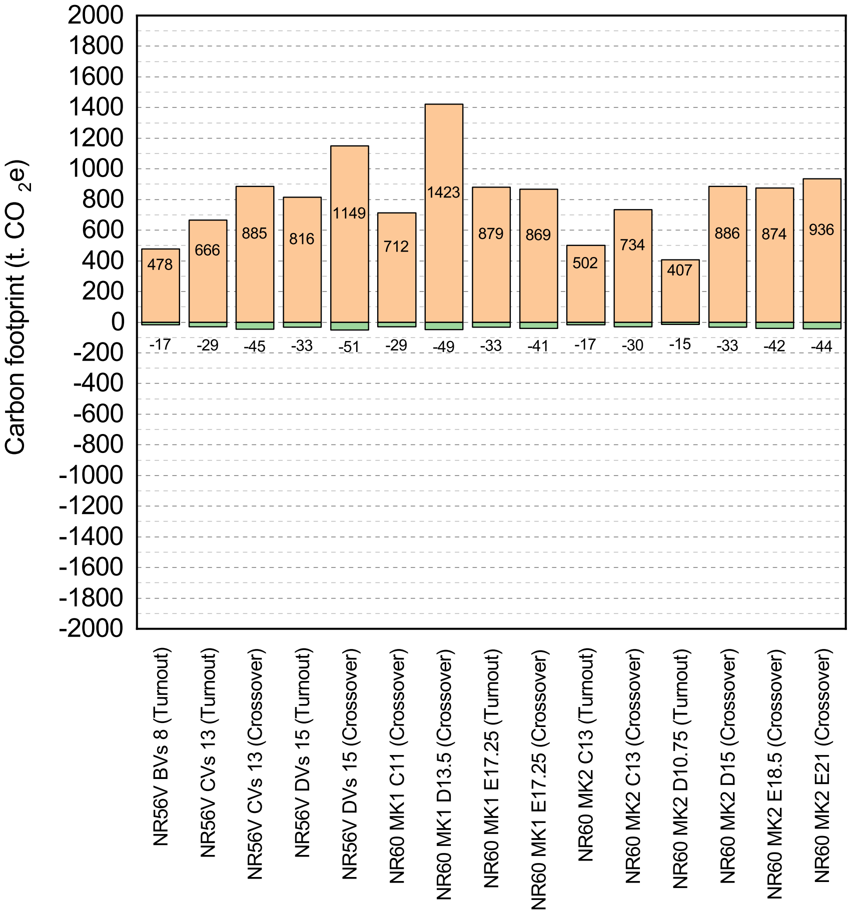


FIGURE 5.10: Carbon footprint for 60-year lifecycle. Scenario: *A*.

In scenario *B*, it was intended to replicate the potential benefits of improved sub-structural performance, offered by the Mark 1 and Mark 2 variants, this was done by assuming that the maintenance cycle for railway ballast is halved and its scheduled renewal is completed after 40 years of operation (instead of 20 years).

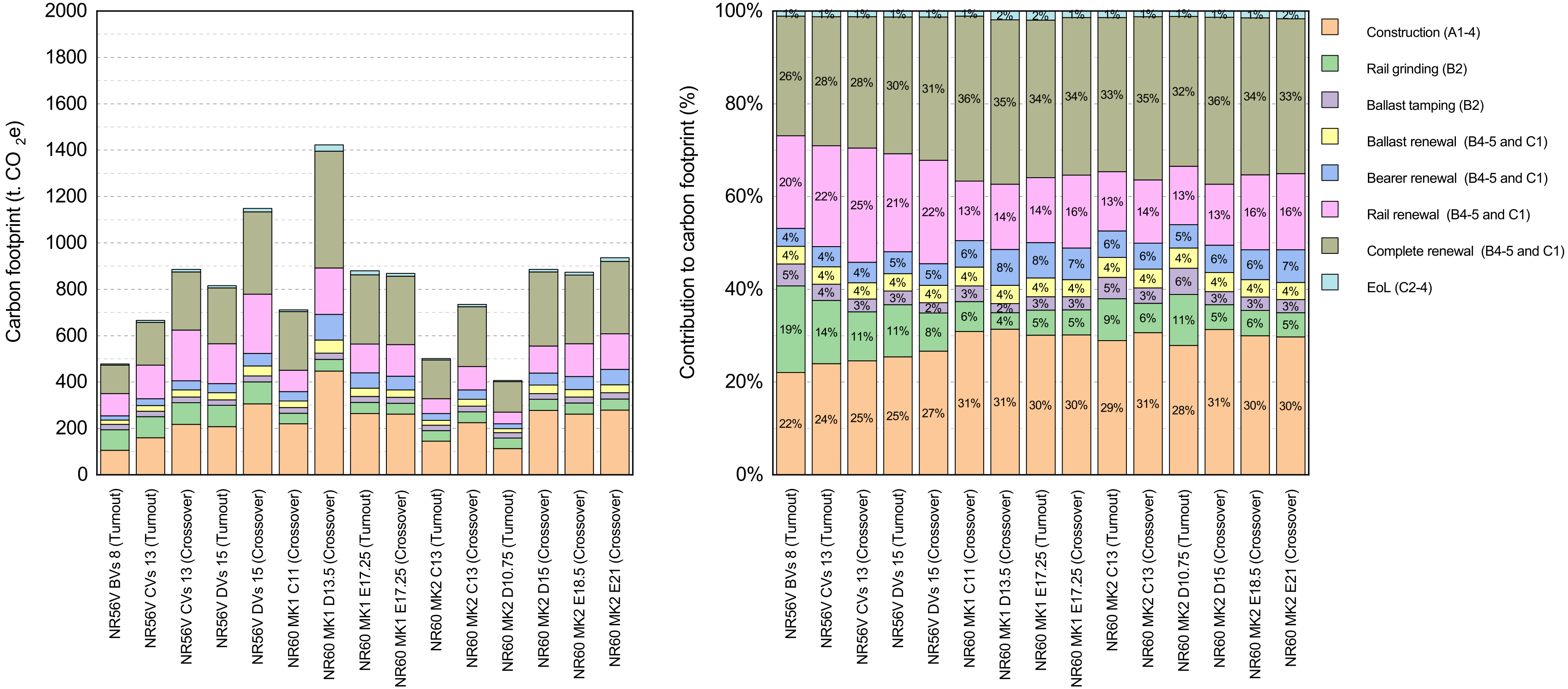


FIGURE 5.11: Carbon footprint per lifecycle stage. Scenario: *A*.

These cycles are selected to observe whether such an exaggerated improvement in performance will yield any meaningful benefits in terms of reduced GHG impact. When comparing the total impacts for each design (Figure 5.12) against those from scenario M (Figure 5.8), it is found that the improvement (for the Mark 1 and Mark 2 designs) is negligible. In detail, after a 60-year period, the average reduction in their carbon footprint is between 2.9% to 4.1% (or c. 21.9 to 50.7 $t.CO_2e$).

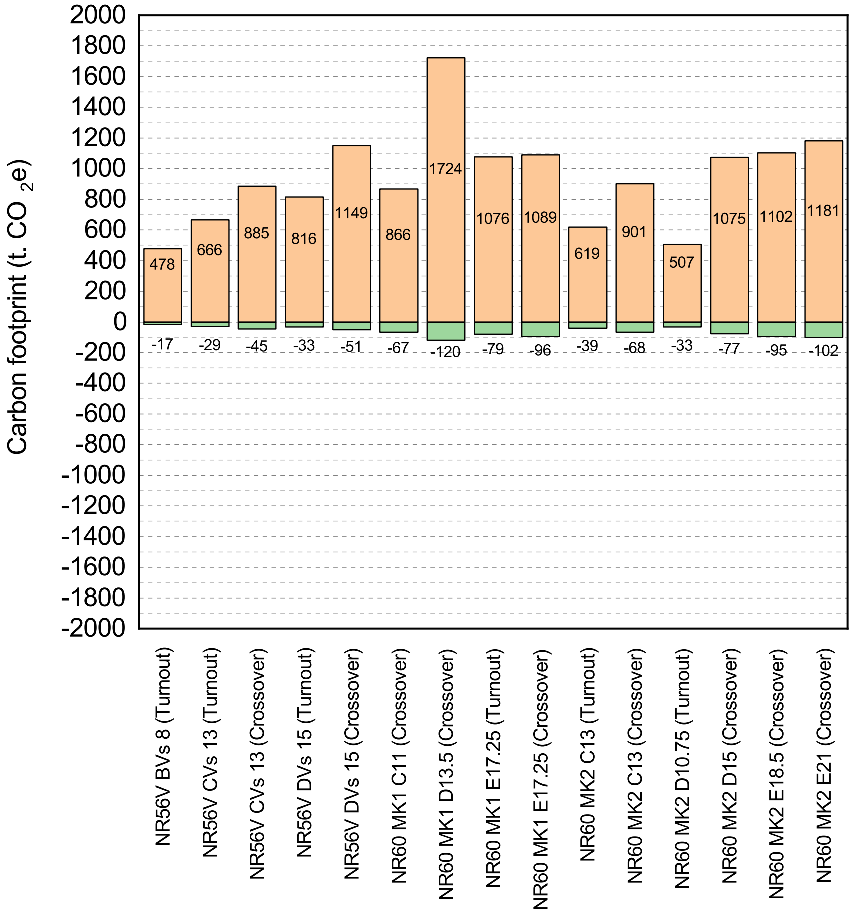


FIGURE 5.12: Carbon footprint for 60-year lifecycle. Scenario: B.

In scenario C, the potential cumulative benefits to the track super-structure and sub-structure were examined, by assuming that the maintenance and renewal needs for the Mark 1 and Mark 2 designs are halved for all components (except for sleepers and bearers). This scenario broadly reflects the combined benefits from scenarios A and B. Comparing the total GHG emissions for scenario C against those of scenario M, it is found that the improvement is significant (Figure 5.13), with the average reduction being around 24.9% (22.7% to 27.2%) across the examined designs. In detail, this improvement in absolute terms is around 143.9 to 402.8 $t.CO_2e$), depending on the design considered.

Comparing again equivalent turnouts (Figure 5.13), it is found that the NR60 Mark 2 C13 turnout, has 28.4% lower total footprint than the equivalent NR56 vertical turnout (c. 189 $t.CO_2e$ in absolute terms). This difference was of course, a direct result of the reduced maintenance and renewal requirements between the two designs. If the intervention cycles

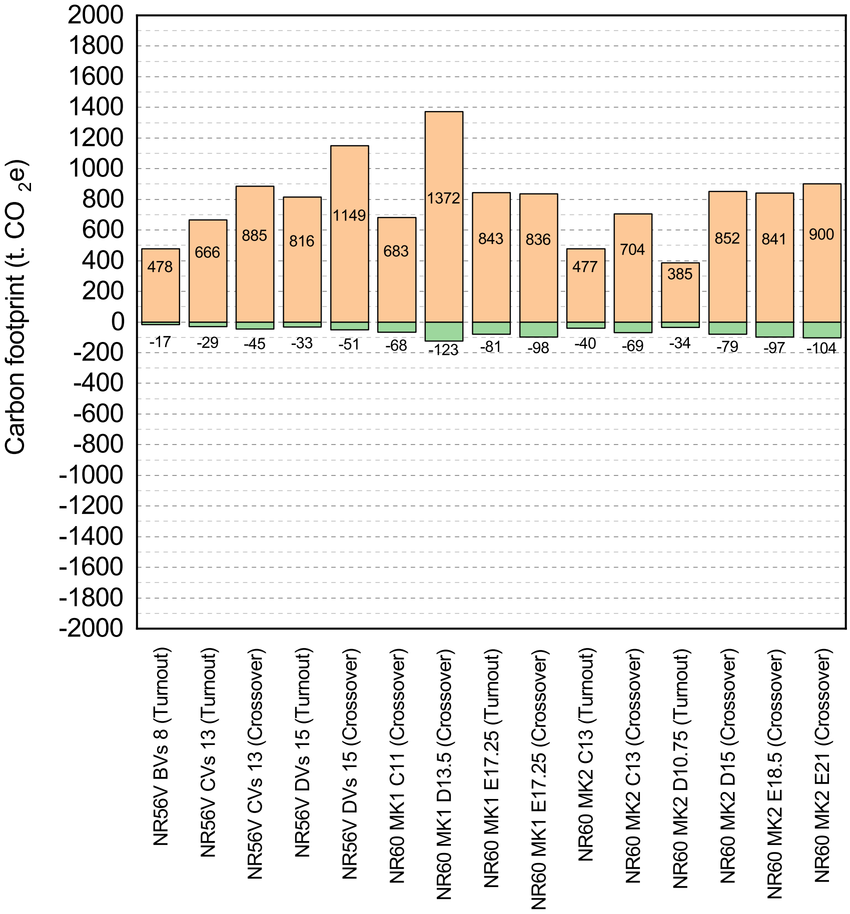


FIGURE 5.13: Carbon footprint for 60-year lifecycle. Scenario: *C*.

were identical (as in scenario *M*), the difference in lifecycle GHG emission, would be around 3.5% or 22.5 $t.CO_2e$ in absolute terms. Similarly, when comparing equivalent crossovers, the NR60 Mark 2 C13 and D15 crossovers have a lower total footprint by about 20.4% (181.0 $t.CO_2e$) and 25.9% (297.5 $t.CO_2e$), respectively, compared to their equivalent NR56 variants.

Considering the breakdown of these emissions per lifecycle stage (Figure 5.14), renewal actions displayed once again the highest contribution, accounting for about 59.0% of the total footprint. Of these emissions, complete renewals had the highest average share (33.3% or 123 to 504 $t.CO_2e$), followed by rail (17.1% or 51 to 256 $t.CO_2e$), bearer (5.9% or 18 to 110 $t.CO_2e$) and ballast renewals (2.6% or 9 to 43 $t.CO_2e$). Construction of the track had the second highest average contribution to the total footprint, accounting for about 29.1% or 105 to 447 $t.CO_2e$, depending on the design considered. Conversely, track maintenance actions were found to have a minor average contribution to the carbon footprint of each design after a 60-year period, accounting for about 10.8%. The highest share of these emissions was by rail grinding (8.6% or 45 to 95 $t.CO_2e$). Whereas, S&C tamping accounted for just about 2.2% of the total GHG emissions or 11 to 25 $t.CO_2e$ in absolute terms. Finally, EoL was found to account for around 1.1% of the total footprint (between 3.3 to 18.1 $t.CO_2e$).

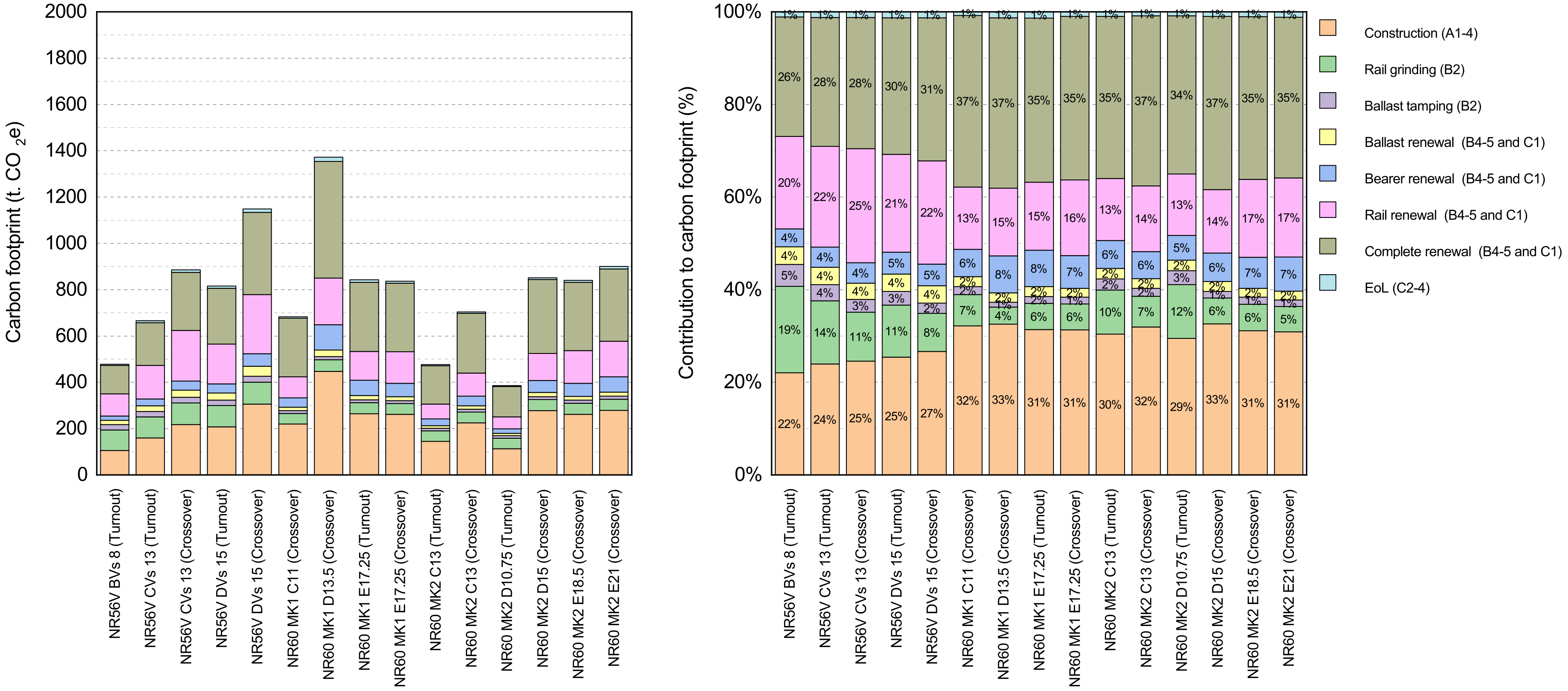


FIGURE 5.14: Carbon footprint per lifecycle stage. Scenario: *C*.

Scenario : COVID – 19

The second group of scenarios also assumed that the transport of materials and labour to and from the site is made by road as in the BAU scenarios. As above, each individual scenario (M_1 to C_1) examines the same options with respect to maintenance and renewal intervention cycles for different components (Table 5.6). However, in this set of scenarios, it was assumed that car sharing and hotel stays of labour are restricted, this was done to broadly simulate a 'worst case' travel scenario due to the COVID – 19 pandemic. Starting by comparing the results of scenario M_1 (Figure 5.15) against those of scenario M (Figure 5.8), it can be seen that the increase in emissions between the two scenarios is between 20 to 71 $t.CO_2e$, depending on the design examined. These figures translate to an average increase in GHG emissions of around 3.3% to 5.3%.

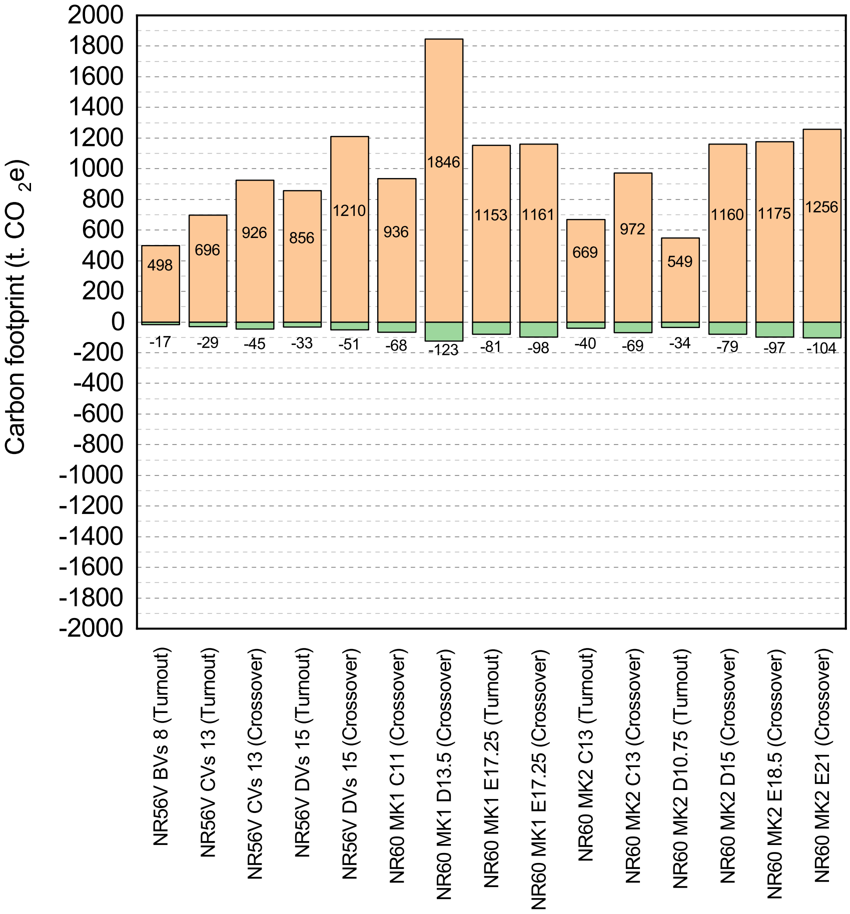


FIGURE 5.15: Carbon footprint for 60-year lifecycle. Scenario: M_1.

When these emissions are broken down per lifecycle phase (Figure 5.16), the highest contribution is made by the renewal activities (62.2%), with complete and rail renewals having an average contribution of 27.0% (127 to 516 $t.CO_2e$) and 26.2% (103 to 526 $t.CO_2e$), followed by bearer (4.9% or 20 to 115 $t.CO_2e$) and ballast (4.2% or 23 to 75 $t.CO_2e$) renewals.

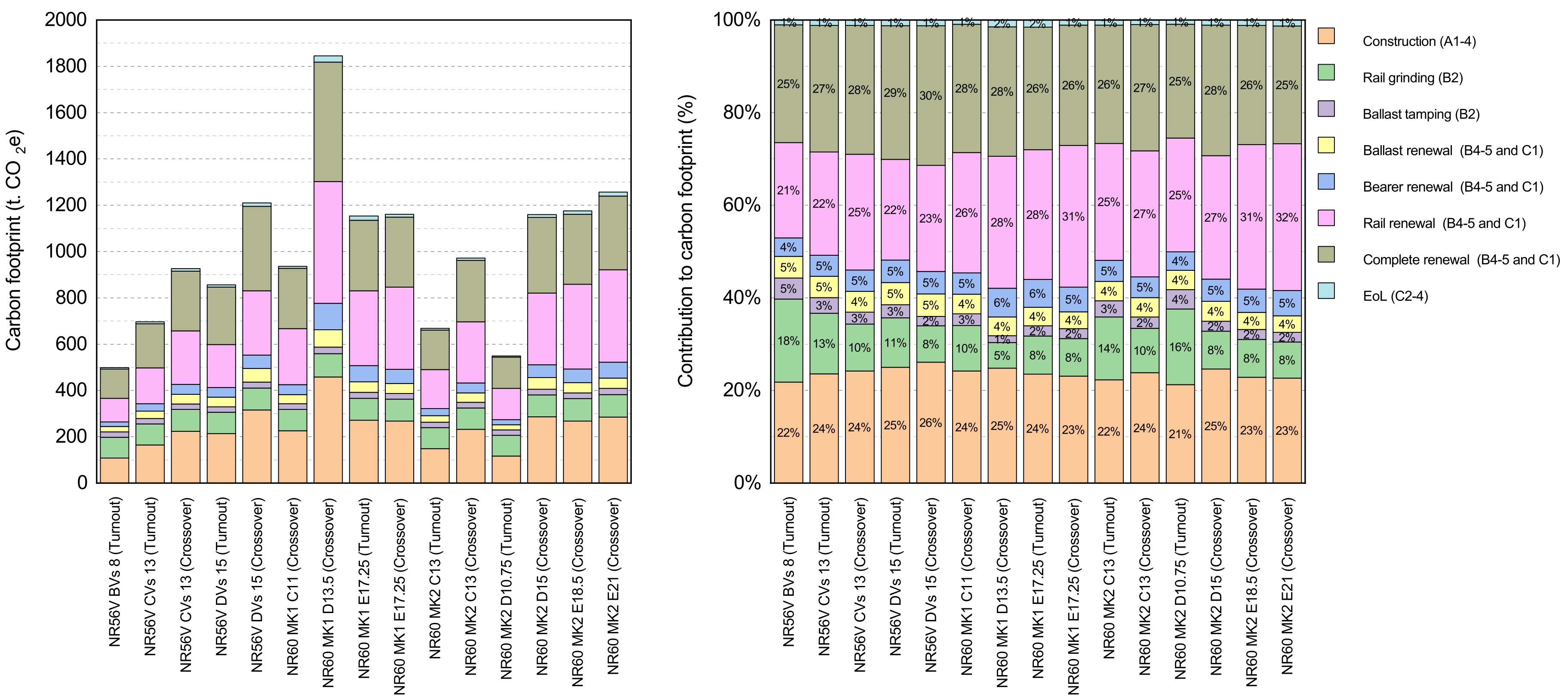


FIGURE 5.16: Carbon footprint per lifecycle stage. Scenario: M_1.

The construction phase is again next on the list, accounting on average for about 23.6% of the total footprint, which translates to 109 to 458 $t.CO_2e$, depending on the design examined. Track maintenance actions have a modest average contribution of around 13.0%, which translates to about 112 to 129 $t.CO_2e$ after a period of 60 years. Finally, the EoL phase, has once again, a minor contribution to the total footprint, averaging a figure below <2%.

The differences between the results of this scenario and the BAU stem from the fact that both car sharing and hotel stays are restricted, which translates to a higher number of total trips required for each work activity. In detail, labour transport leads to an increase of the total impact of rail renewals (7.0 to 24.7 $t.CO_2e$), complete renewals (3.3 to 11.6 $t.CO_2e$), construction (3.3 to 11.6 $t.CO_2e$), ballast (5.1 to 18.1 $t.CO_2e$) and bearer renewals (1.4 to 4.9 $t.CO_2e$). It is worth noting, that the minimum and maximum increases between work activities, are driven directly by the total site possession times (incl. breakdown for each sub-activity) and the number of shifts required for each sub-activity.

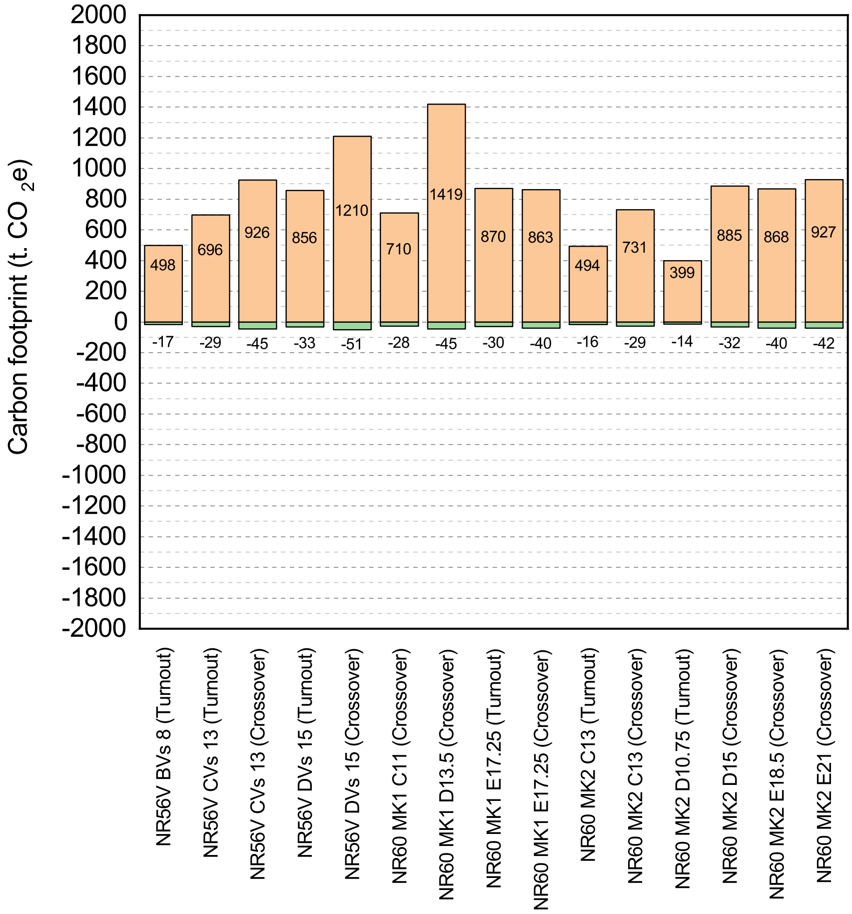


FIGURE 5.17: Carbon footprint for 60-year lifecycle. Scenario: C_1.

In scenario C_1, the same assumptions with respect to maintenance and renewal cycles have been applied, as in scenario C. The only difference between the two scenarios is with respect to the car sharing and hotel stays of labour, which are once again restricted. This scenario examines the potential cumulative benefits to the track super-structure and sub-structure from the introduction of the Mark 1 and Mark 2 designs. Comparing the results of this scenario

(Figure 5.17) against those from scenario M_1 (Figure 5.15), it was found that the Mark 1 and Mark 2 designs had an average reduction in their footprint of about 23.1% to 27.4%, which translates to approximately 150.6 to 426.8 $t.CO_2e$, depending on the design selected.

Considering the breakdown of these emissions per lifecycle stage (Figure 5.18), unsurprisingly, renewal actions remain as the highest contributing processes within the lifecycle of S&Cs, having an average contribution of around 59.7% (222 to 878 $t.CO_2e$). Similarly, construction has a major contribution to the total lifecycle emissions for each design, accounting on average for around 28.8% (109 to 458 $t.CO_2e$). Track maintenance actions had again a modest contribution, with rail grinding having the highest share of these emissions (8.2% or 45 to 95 $t.CO_2e$), followed by ballast tamping, which only accounted for around 2.1% (11 to 25 $t.CO_2e$) of the total carbon footprint. The EoL phase once again barely contributed to the lifecycle GHG emissions by contributing on average for around 1.1% of these emissions.

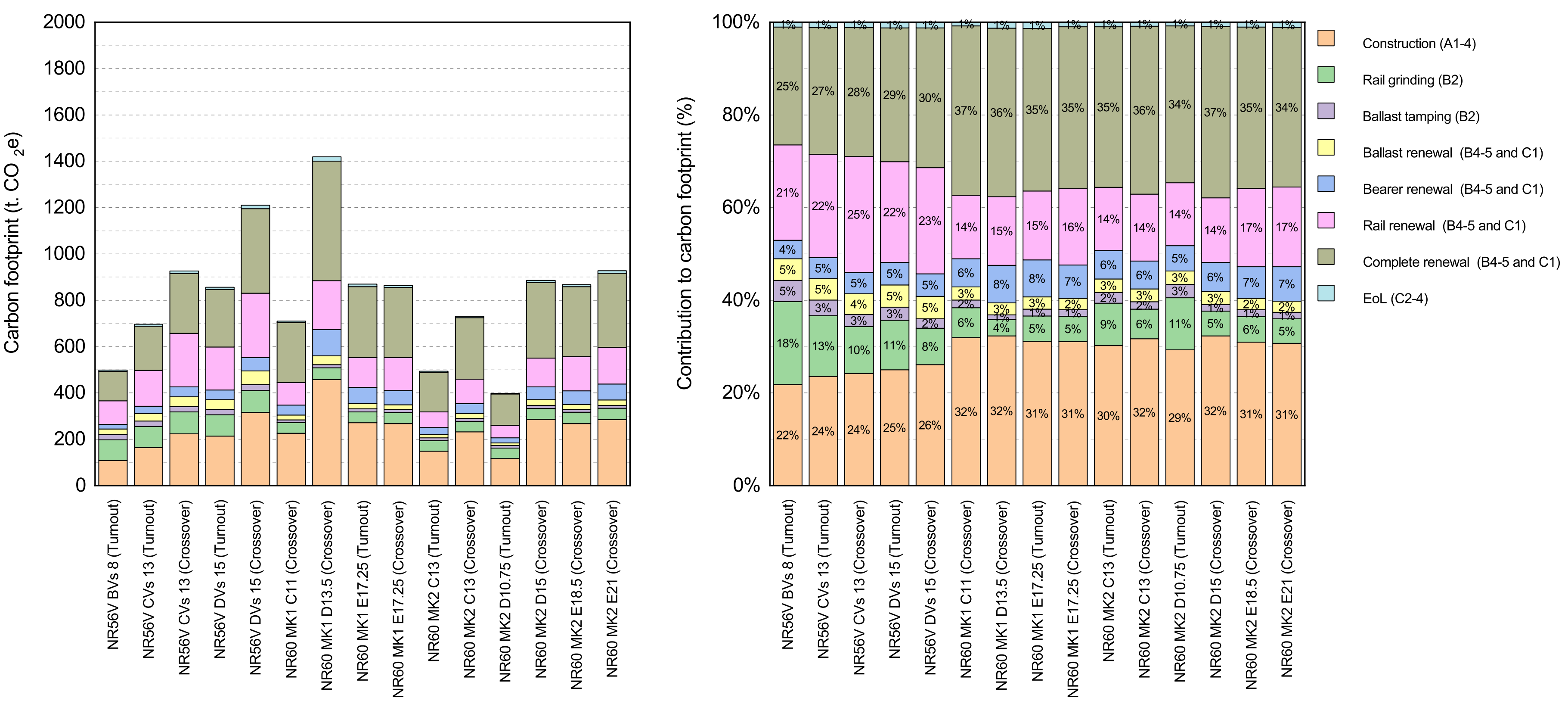


FIGURE 5.18: Carbon footprint per lifecycle stage. Scenario: C_1.

Scenario : Modal Shift from Road to Rail

The final group of scenarios was tested to simulate the potential improvement in performance from a projected modal shift from road to rail for transporting materials, labour and plant. As with the previous sets of scenarios, each individual scenario (M_2 to C_2) examines the same options with respect to maintenance and renewal intervention cycles for different components (Table 5.6). Starting by comparing the results of scenario M_2 (Figure 5.19) against those of scenario M (Figure 5.8), it can be seen that the modal shift assumption, results to a modest reduction of the total emissions of between 19.4 to 75.2 $t.CO_2e$, depending on the design examined. These figures represent a reduction in the lifecycle footprint of around 3.6% to 5.0%.

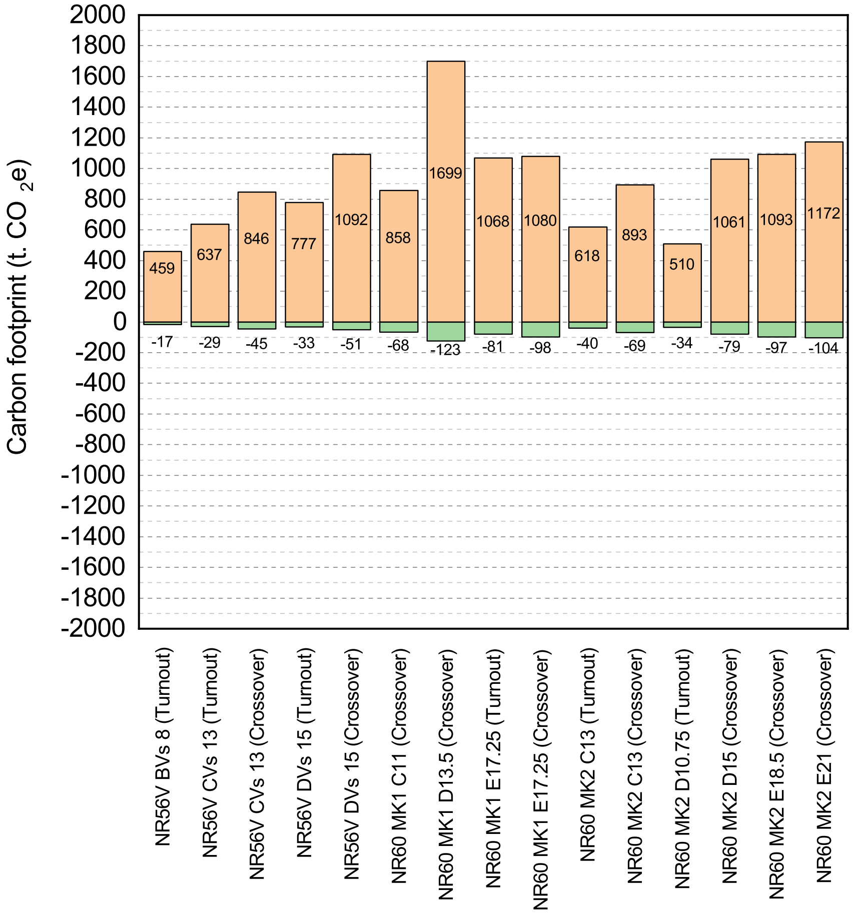


FIGURE 5.19: Carbon footprint for 60-year lifecycle. Scenario: M_2.

Similarly, when comparing the results of scenario C_2 (Figure 5.20) against those of scenario C (Figure 5.13), it was found that the assumption of shifting from road to rail, led to an average lifecycle emissions reduction of around 3.8% (between 3.2 to 5.8%), which translated to between 13.0 to 57.2 $t.CO_2e$ less GHG emissions over a 60-year period.

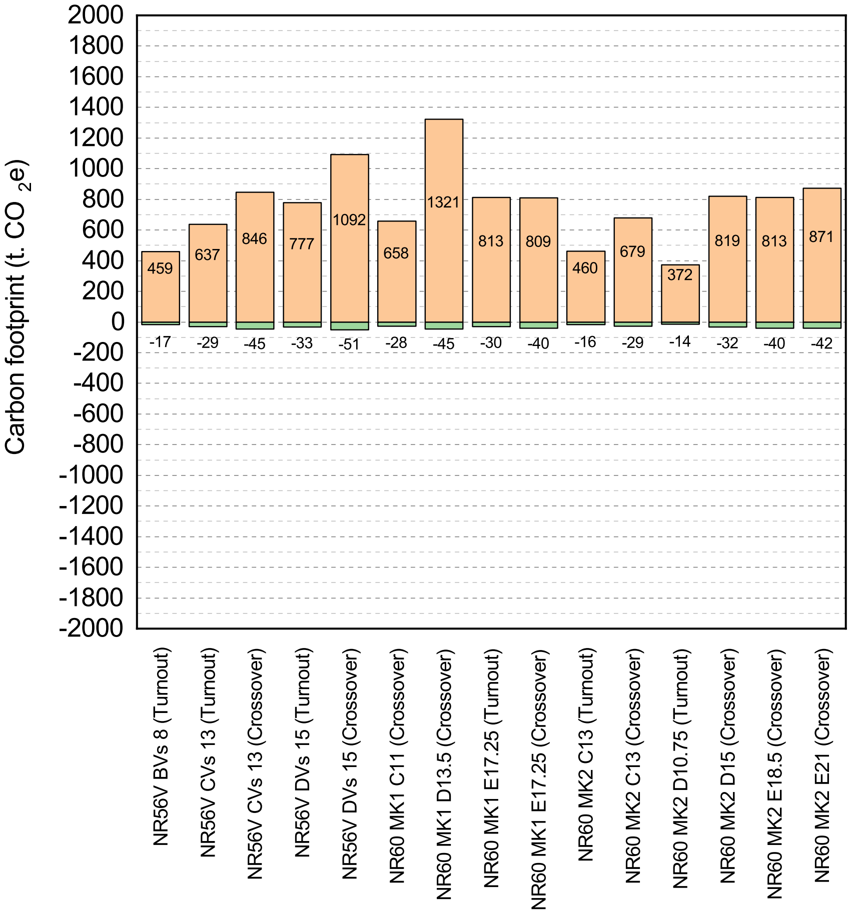


FIGURE 5.20: Carbon footprint for 60-year lifecycle. Scenario: C_2.

5.3.2.3 Carbon Footprint Costs

Once the GHG emissions resulting from each scenario have been quantified, these are given a monetary value. Considering this, the carbon values (in 2021 prices) given by the DfT (2022) are used to monetise the changes in emissions from each option. For these calculations, the base year for discounting is 2021, with the base test discount rate taken as 3.5% for the first 30 years of the appraisal and a lower discount rate of 3.0% used thereafter (as recommended by HM Treasury (2018)).

On this section only scenarios *M* and *C* will be examined. Scenario M assumes that the NR60 Mark 1 and Mark 2 designs will have identical performance to that of the benchmark variants. Whereas, scenario *C* attempts to replicate the claimed benefits (for both the super-structure and the sub-structure) of these designs. It is worth noting, that the designs to be compared are normalised on a per metre of single track basis, in an attempt to eliminate certain issues deep-rooted within the input data. As mentioned earlier, the data inputs, which form the basis of the activity data, are sourced from specific project installations, where potentially more materials/components were needed for specific sites. Thus, by normalising on a per metre of single/double track, such potential inconsistencies can be accounted for.

Given the differences in switch sizes, crossing angles and layout types, it is only feasible to make a limited number of comparisons for each scenario. Considering scenario M, it is found that the use of the NR60 Mark 2 C13 turnout, instead of the NR56 CV13 turnout can bring a dis-benefit of -£88, -£175, -£263 per metre of single track installed. Similarly, the choice of NR60 Mark 2 C13 crossover instead of the NR56 CV13, results to a dis-benefit of -£154, -£307, -£461 per metre. Likewise, the use of NR60 Mark 2 D15 crossover instead of the equivalent NR56 DV15 design, results to a dis-benefit of -£244, -£488, -£732 per metre of track installation. Based on these results, assuming that the track performance is equal across designs, it is found that when these designs are normalised per metre of installation, the use of the newer NR60 Mark 2 variants result to worse performance than the benchmark designs. Adding to this, the carbon cost di-benefits from their use amplifies with respect to their switch size and crossing angle. Meaning that the bigger the size of the switch and the higher the crossing angle, the bigger is the resulting carbon cost dis-benefit per metre of track installed.

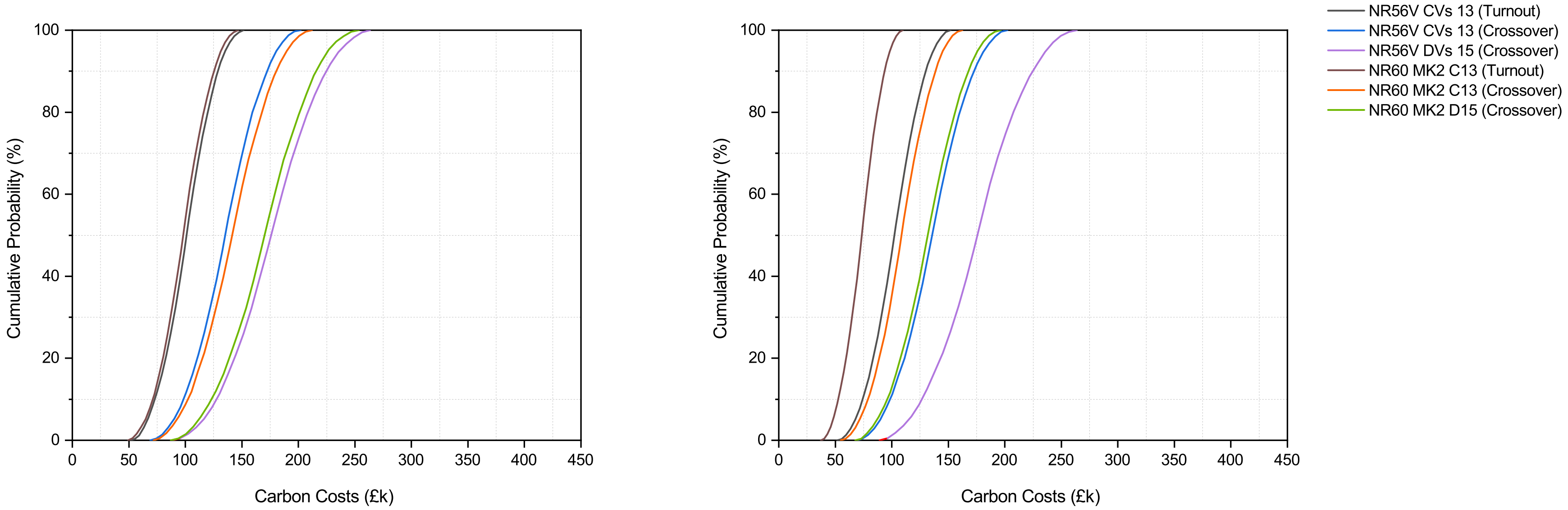
Considering scenario *C*, it is found that the use of the NR60 Mark 2 C13 turnout, results to a carbon cost benefit of £120, £240, £360 per metre of track installed. Similarly, when the NR60 Mark 2 C13 crossover is installed instead of the equivalent NR56 v design, there is a resulting carbon cost benefit of c. £30, £60, £90 per metre. Conversely, even when accounting for the performance benefits to the super-structure and sub-structure from the use of the NR60 Mark 2 designs, these are not sufficient to reverse the environmental impact of the NR60 Mark 2 D15 crossover (when compared to the NR56 v D15), resulting to a carbon cost dis-benefit of c. -£59, -£119, -£178 per metre of installation. However, it is important to note here, that in absolute figures, the NR60 Mark 2 D15 crossover, displayed a better performance compared to its equivalent NR56 v design and that it is possible that the figures presented here are not representative of every installation. Meaning that it may be that when these designs are installed at different sites, the NR60 Mark 2 D15 crossover may lead to a carbon cost benefit instead of a dis-benefit, when compared to its equivalent benchmark crossover.

As in Chapter 4, it is worth highlighting that there are some inherent risks associated with the economic evaluation of the costs of CO_2e. Thus, in order to overcome this, a stochastic approach has been selected. This has been done once again by conducting a MCS (Kalos and Whitlock, 2008) using the same approach as in Chapter 4. The goal of the adopted method was to assess the risk associated with these estimates, choosing randomly modifiable values in each iteration. In terms of simulation details, MCS samples were of size 10,000 for each of the models. It was assumed that the evaluated annual cost of carbon is a triangularly-distributed random variable; with the minimum, maximum, and mode being calculated based on the target-consistent marginal abatement costs given as a three-point estimate by DfT (2022). The cumulative probability distribution curves for each S&C variant for scenarios *M* and *C* are displayed in Figure 5.21 below.

A number of conclusions can be drawn from the results of the MCS presented in Figure 5.22. First, for both scenarios M and C, the expected lifecycle carbon costs for each turnout are found to be lower than their equivalent crossover (in terms of switch size and crossing angle). Moreover, for the former scenario (M) there is a higher uncertainty than the latter (C) for the carbon costs estimates of the Mark 1 and Mark 2 designs as it can be inferred from the higher width, and flatness of their S-Curves, indicating higher standard deviation (σ).

Secondly, when comparing equivalent designs (Figure 5.21) for the baseline scenario M, the differences between their lifecycle carbon costs are found to be marginal, which is evident by the overlaps between their S-Curves. However, when comparing these designs for scenario C, it is found that the newer Mark 2 designs have significantly lower lifecycle carbon costs, compared to their equivalent benchmark designs. In detail, the NR60 Mark 2 C13 turnout is bringing a lower minimum (£73.4k) and maximum (£109.7k) carbon cost compared to its equivalent NR56 turnout. Likewise, the NR60 Mark 2 C13 crossover results to a lower minimum (£108.8k) and maximum (£162.9k) carbon cost compared to its equivalent NR56 crossover. Similar results are found for the NR60 Mark 2 D15 crossover, which again results to lower minimum (£131.7k) and maximum (£196.6k) lifecycle carbon costs, when compared to its equivalent benchmark crossover.

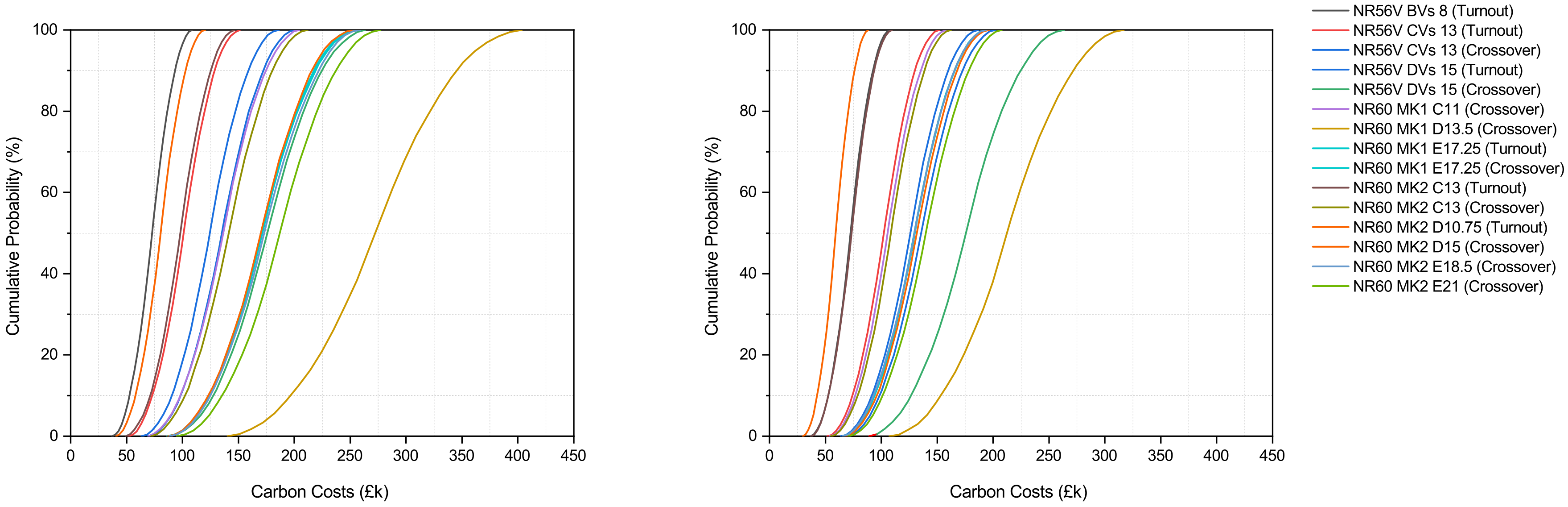
Finally, under scenario C, the expected carbon costs for the NR60 Mark 2 C13 turnout can be set between £52.9k to £93.7k with an 80% probability, and an μ value of £73.3k. Similarly, under the same scenario, the NR60 Mark 2 C13 crossover will have its carbon costs set between £78.0k to £139.1k with an 80% probability, and an μ value of £108.6k. Whereas, the expected carbon costs for the NR60 Mark 2 D15 crossover can be set between £94.5k to £167.7k at the same probability, and an μ value of £131.7k.



(A) Scenario : *M*

(B) Scenario : *C*

FIGURE 5.21: Costs of carbon dioxide cumulative distribution function for equivalent design variants.



(A) Scenario : *M*

(B) Scenario : *C*

FIGURE 5.22: Costs of carbon dioxide cumulative distribution function.

5.4 Conclusions

This study evaluated and compared the lifecycle GHG emissions associated with fifteen S&C (six turnouts and nine crossovers) design variants used in the UK railway network. The chapter builds upon the modelling framework presented in Chapter 4, extending its capabilities by integrating a detailed LCI, which is tailored around a number of older and newer S&C designs used in the UK. The modelling framework, permits the 'cradle-to-grave' appraisal of different S&Cs from a whole-life carbon and cost perspective. It estimates the embodied material, process and transport emissions, linked with the lifecycle activities of construction, maintenance, renewal, EoL, as well as the benefits and burdens beyond the system boundary selected for this case study.

Based on the results of this chapter the following conclusions can be drawn. Firstly, considering the construction of an S&C, it has been found that plant and machinery had the highest average contribution to these emissions, ranging between 43.04% to 45.4%. The impact of materials and components was found to be the second highest (37.02% to 39.00%). Transport of materials, plant, machinery and labour was found to have the least average contribution of between 15.5% to 19.93%. The total GHG emissions from this phase was found to range between 102.4 to 458.2 tonnes of CO_2e, depending on the scenario and design selected. When comparing the impact of constructing a crossover against its equivalent turnouts (in terms of design specification, switch size and crossing angle), it was found that on average the former has 24.8% to 46.8% larger carbon footprint than the latter. When considering the whole-life carbon footprint of turnouts and crossovers, this difference is set further apart, with crossovers having on average, 25% to 31% higher carbon footprint.

Secondly, it is found that parameters such as crossing angle and switch size influence the lifecycle carbon footprint of S&C designs, with higher crossing angles and switch sizes, resulting on average to a larger total footprint. It is worth noting, that there were some cases, where designs with a smaller switch size and crossing angle (e.g. NR60 Mark 1 D13.5), resulted to a higher total footprint (in absolute terms). This is most likely tied to the fact that the data inputs for the LCI are based on activity data from specific UK installations, where more materials/components were necessary for these particular sites, resulting to inconsistent outcomes from the analysis.

Thirdly, when looking at equivalent designs, on average the NR60 Mark 2 variants, display marginally better performance in terms of lifecycle GHG emissions, when compared to their equivalent NR56 vertical designs. This is assuming that, irrespective of design characteristics and track performance, all designs have identical maintenance and renewal requirements. However, when the cumulative benefits to the super-structure and sub-structure from the introduction of the Mark 1 and Mark 2 designs are accounted for, It is found that these designs display a significant improvement in environmental performance, displaying an average reduction in their total footprint of around 24.9%. This translates in absolute terms at around 102.8 to 143.9 tonnes of CO_2e, depending on the design considered. These significant improvements maximise the environmental benefits of the newly introduced Mark 2 designs, resulting at a lower carbon footprint by about 24.9% (on average).

Fourthly, when considering the breakdown of the whole-life carbon footprint by LCA phase, it is found that the impact of track renewals is the highest (ranging between 58.7% to 62.2%), followed by the phases of construction (23.6% to 29.1%) and maintenance (10.4% to 13.6%). Whereas, the EoL phase had the lowest average contribution, with a figure below 2.0%, irrespective of the scenario considered.

Finally, this work also included an LCC analysis of these layouts. However, due to data limitations, this was only focused on carbon costs, disregarding CapEx and OpEx. Nonetheless, the model is capable of performing a full LCCA, if data becomes available in the future. Based on the results, the following conclusions can be drawn. First, when assuming that the track performance is identical across designs, it is found that the use of NR60 Mark 2 variants, results to carbon cost dis-benefits when compared against their equivalent NR56 vertical designs. These dis-benefits were found to amplify with bigger switch sizes and higher crossing angles. Second, irrespective of the scenario examined, the expected lifecycle carbon costs for each turnout are found to be lower than their equivalent crossover. Finally, when the performance benefits for the newly introduced NR60 Mark 2 designs are been accounted for, their use results to a carbon cost benefit per metre of track installed. However, these benefits scale down for layouts with bigger switch sizes and higher crossing angles.

Chapter 6

Case Study III: Route appraisal

6.1 Introduction

Tests can be carried out on elements of railway track in a laboratory to assess the potential for particular ballast and sleeper combinations to alter stiffness, reduce settlement, and improve the transfer of stresses between sleeper and ballast. For example, a number of modifications to the ballasted track have been shown to reduce settlement in such tests. However, it is more problematic to apply test results to predict real world field rates of deterioration along the track geometry which is largely a function of differential settlement. This is important, because an understanding of reductions in real world rates of deterioration is necessary to predict the whole life carbon footprint and LCC of such interventions and assess the socio-economic case for altering current practice.

Against this background, this chapter examines the impact of installing a number of novel interventions on two different routes in the UK. A methodology, based on relative settlement is proposed to adapt the results of laboratory element tests into a suitable parameter for input into the track geometry degradation model, allowing estimation of the carbon footprint and LCC. The whole-life carbon and cost model presented in this Chapter, builds upon the principles of the framework presented in Chapter 4 and 5.

First, the relationship between settlement and geometry deterioration is discussed. Second, laboratory tests carried out with different interventions are described and a method to adapt these results is presented. Third, a modelling framework is developed for environmental and financial appraisal of modifications to the ballasted track at the route level. Fourth, test results are applied to two practical case studies. Finally, conclusions from the studies are presented. Although the conclusions of this chapter are based on a UK case study, they could be applicable to any ballasted railway track operation in a developed region facing high maintenance costs and growing demand.

6.2 Methodology

6.2.1 Settlement and geometry deterioration

Ballast provides a stable support to the track reacting against the vertical and horizontal forces applied by trains and providing a free draining medium. Ballast is often the main locus of track settlement although this depends on the local subsoils present (Yoo and Selig, 1979). Figure 6.1 shows the typical relative contributions of substructure layers to track settlement with a good subgrade soil foundation (Selig and Waters, 1994).

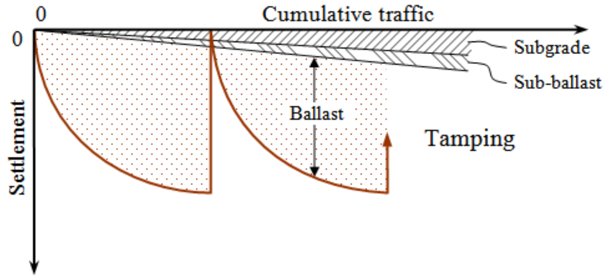


FIGURE 6.1: Substructure contributions to settlement (adapted after Selig and Waters (1994)).

If the track settled uniformly along its length according to Figure 6.1 this would not cause any difficulties for performance. However, non-uniform or differential settlement of the supporting substructure develops as a function of cyclic loading (axle passes). If left uncorrected, the track geometry will deteriorate as loading continues, affecting the ride quality and eventually the safety of train operation, and also resulting in higher train operating costs through increases in train maintenance and fuel consumption (Sasidharan et al., 2020). Therefore, it is necessary to periodically correct the track geometry. To return the track to its design line and level, ballast needs to be maintained, usually by mechanised tamping. Tamping is a process which consists of lifting the track and squeezing the ballast under the sleepers to fill the space generated. However, tamping causes ballast particle breakage with fines generation thus decreasing ballast performance over time.

The rate of track geometry deterioration can vary significantly from site to site depending on, for example: local geology, the track form, the frequency and variability in axle load and train speed, the age of track components and the number of prior maintenance tamps. Current industry practice is to measure the track geometry regularly, using specialized track recording vehicles that rely on either chord or inertial measurement systems. Recorded track geometries are converted to a relative offset from the idealised geometry over an appropriate wavelength (35 m, 70 m or 150 m). The SD of the measured geometry for particular lengths of track (e.g. per 1/8 mile in the UK) gives a measure of the track quality. The measured geometry is evaluated against industry standards for maintenance requirements, both globally in the sense that a length of track may require maintenance or renewal if the SD reaches a certain level; and locally for geometry trigger exceedances that may require more urgent or even emergency remediation works. In such cases, speed restrictions or line closures are put in place, potentially resulting in reactionary delays across the system or in service diversions or cancellations.

Records of how the track quality (SD) changes over time or with cumulative tonnage allow empirical predictions of future maintenance needs to be made. Such predictions are usually based on an assumed linear or logarithmic deterioration of SD with time or cumulative tonnage, and may take account of the degree of ballast fouling (process by which the voids between particles become filled with fouling material) and the increased frequency of maintenance needed as damage to the ballast accumulates.

Because predictions are empirical, any relationships used must 'lump together' a number of local effects such as geology, hydrogeology, weather, ballast, sleeper type, earthworks and more. For example, the prediction method used by NR includes a LTSF (SERCO, 2007), which scales the general form of the logarithmic track quality deterioration function to local historical records. The LTSF may also be used to forecast the effects of a given improvement (e.g. the provision of USP at a renewal) by reducing the factor (see Ortega et al. (2018b)). However, the evidence on which to base any such adjustment to the LTSF is often lacking, hence the need for more research and field trials. The effect of fouling may also be incorporated into such predictive tools to show its influence on increasing rates of geometry deterioration. However, functions to calculate the influence of fouling are difficult to implement accurately owing to the diversity of effects different fouling regimes can have on a range of ballasts (Federal Railroad Administration, 2020; Rohrman et al., 2020). Common sources of fouling are (1) fines generated from tamping (2) environmental fouling transferred into the ballast as a surface contaminant (e.g. spoil falling from open freight wagons) or (3) by migration into the ballast from a poor subgrade. In its worst case, this latter source leads to mud pumping (Hudson et al., 2016). Modern track construction and renewal methods aim to eliminate subgrade sources of fouling by suitable track bed thickness design that may include the provision of sand-blankets and geotextile filters and suitable drainage. Sources of environmental fouling are also less common in railways using modern operating practices, because freight wagons are more usually covered and spoil is not able to fall into the track bed.

More recently practitioners and researchers have postulated a link between track support stiffness and geometry deterioration (Grossoni et al., 2019; Hunt, 2000; Le Pen et al., 2020; Sussman et al., 2001; Woodward et al., 2014). The mechanism of track geometry deterioration implied by linking it with track bed support stiffness may be understood by considering what the train 'sees' of the track bed support stiffness. As far as a train is concerned, if the load remains uniform and the support stiffness does not change and is continuous beneath the rail, the wheel sits within the deflected profile of the rail and remains unaware of the support stiffness except when that stiffness changes or when the load changes. Varying track support stiffness therefore gives rise to dynamic increments of load which may in turn drive further differential settlement and apparent changes in support stiffness as support levels change along the track. Attempts have been made to evaluate the influence of varying support stiffness on changes in the load by the use of vehicle track interaction models (VTIs) and also sometimes to implement settlement rules using the modelled load outputs over many cycles to evaluate the effect of differential settlement in an iterative modelling procedure to predict geometry and maintenance needs into the future (Nguyen et al., 2016; Oscarsson, 2002b,a). However, although these studies provide insights, they are hampered by both a lack of support stiffness measurements correlated to track geometry and the lack of a generally applicable settlement equation that allows for all the possible input variables (Abadi et al., 2016).

Track support stiffness is made up of various parts including the effect of rail pads, ballast and sub-ballast, but it is often globally modelled as a simplified equivalent elastic spring per sleeper end or rail support or, if normalised per length of track as a modulus continuously supporting an infinite beam – the rail (Esveld, 2001; Raymond, 1985; Timoshenko, 1927). Based on these principles, the recently published Guide to Track Stiffness (Powrie and Le Pen, 2016) sets out the mathematical framework and describes the various ways in which stiffness can be defined, how to allow for the effects of different components and how to convert between the different definitions.

6.2.2 Laboratory Tests

The Southampton Railway Testing Facility (SRTF) was used to investigate the response of different combinations of sleepers and ballast to cyclic loading, over millions of load cycles representative of axle loads in Europe and elsewhere. The detailed test results are reported in Abadi et al. (2018, 2019) and Ferro (2018) and only a brief description of the tests and selected outputs of the tests relevant to the current study are included in this chapter.

The SRTF is a test bay comprising one concrete mono-block sleeper on a 300 mm ballast bed underlain by rubber matting to represent a subgrade. The side walls are held at a fixed distance of 0.65 m apart, corresponding to a typical UK sleeper spacing to maintain conditions as close to plane strain as possible. The test is carried out on a strong floor and an overhead loading frame and actuator arrangement imposes a sinusoidal cyclic loading at 3 Hz through a spreader beam on top of short rail sections mounted on the sleeper in the usual rail fixing locations.

Figure 6.2 shows a cross section of the key features of the test set-up. At the base of the ballast bed a 12 mm thick rubber mat represents a slightly compressible subgrade. Its thickness was chosen so that the cyclic deflection of the sleeper reached realistic values (up to 1 mm) during testing.

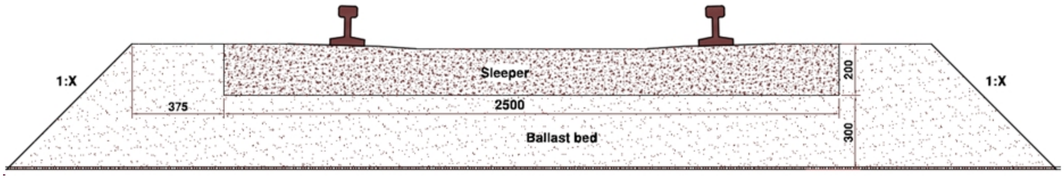


FIGURE 6.2: Test cross-section through a typical test set-up (Abadi et al., 2018).

After carefully controlled preparation to maintain repeatability, the test set up is loaded to at least 3 million cycles of an equivalent 20 tonne axle load representing approximately two years of use on a busy line. The detailed testing procedure and results are described in Abadi et al. (2019, 2016), but a summary of the testing carried out on the performance of a number of modifications is provided below.

6.2.3 Railway track interventions

Twin-block sleepers

A twin-block sleeper comprises two concrete blocks, one beneath each rail, tied together by a steel rod. In terms of cost and performance, it is unclear which is better (e.g. twin-block vs. mono-block), and there are strongly held but conflicting views. Twin-block sleepers have been primarily employed in France for both high-speed and conventional lines, whereas, mono-block concrete sleepers are traditionally used in the UK.

Abadi et al. (2019) studied the potential for performance improvement from the adoption of different sleeper types and modifications to the sleeper/ballast interface by carrying out tests in the SRTF apparatus. They showed that twin-block sleepers and USP have the potential to reduce maintenance requirements and whole-life costs. In particular, the use of twin-block sleepers was beneficial in (i) reducing permanent settlement, (ii) preventing centre binding and hogging at increased number of cycles, (iii) improving ballast containment and stability at the edges of the sleeper near the shoulders, and (iv) prevent any significant increase in ballast longitudinal stress at the centre of the track. However, when USP (stiff or soft) were present, these benefits were less pronounced when compared to their mono-block alternatives.

Under Sleeper Pads (USPs)

USP (or performance pads as they are sometimes known) are thin rubber-like sheets fixed to the underside of sleepers. These introduce an added compliance to the system such that under a given load some additional deflection may be present. Field trials and numerical studies of the effect of USP have shown that they have potential to improve track performance. However, the evidence is sometimes contradictory (Ali Zakeri et al., 2016; Le Pen et al., 2018; Paixão et al., 2015; UIC, 2009) and consideration should be given to the particular characteristics of potential deployment sites. For example, for a site where stiffness is already low or changes abruptly, the underlying poor characteristics of the site may still dominate the final behaviour and could even be made worse by the addition of USP. However, in principle, if a variation in stiffness is present along a length of track then by introducing USP the proportion of controlled deflection is increased and hence the potential variation in support stiffness decreases proportionately.

TABLE 6.1: USP data. C_{stat}: static stiffness (given in N/mm^3).

USP	Category of USP	Thickness	Core material	Manufacturers C_{stat} value (N/mm^3)
Type 1 FC500	Stiff	4 mm	Trackelast FC500	0.228-0.311
Type 2 FC208GF	Soft	9 mm	Bonded cork	0.079-0.105

Two types of USP supplied by the company Tiflex were tested and their key properties are given in Table 6.1. Although these USP were supplied by a particular company, they are typical of the USP available and may be categorised respectively as stiff and soft pads (Sol-Sánchez et al., 2015).

Random Fibre Reinforcements (RFRs)

RFRs reinforce ballast by randomly mixing ballast with fibres of selected properties and dimensions. Ajayi et al. (2015, 2016, 2017) used small scale triaxial tests on scaled ballast fibres and sand fibre mixtures to show that there are potential benefits to mixing fibres randomly into a granular mixture provided that the fibre dimensions are appropriately sized in relation to the grain sizes present. To demonstrate the feasibility of using polyethylene fibres in a real application, a test was carried out in the modified SRTF apparatus using the current standard NR ballast grading and fibres with the intention of improving the ballast settlement performance.

Initially the SRTF was used with a batch of ballast sourced from Cliffe Hill quarry, Leicestershire, UK to evaluate the improvement by reinforcing the ballast by fibres that were 300 mm long, 100 mm wide, and 0.5 mm thick polyethylene strips. In this initial test there was approximately 0.2% polyethylene fibre content by weight (Abadi, 2015). Later tests using a second batch of ballast from the same quarry showed that better results could be obtained from 300 mm long, 25 mm wide and 0.5 mm thick fibres at a 0.2% polyethylene fibre content by weight (Ferro et al., 2016). In the SRTF tests, the two batches of Cliffe Hill ballasts conformed to NR specification. However, although the source quarry was the same, slight differences in gradation and possibly source within the quarry meant they performed slightly differently. For this reason the two RFRs ballast tests have their own baseline tests in which the same batch of Cliffe Hill quarry ballast was used for comparison.

Re-Profiled Shoulder (RPS)

In the UK, there is no prescribed standard (with respect to the ballast shoulder slope) and space constraints mean that the ballast often stands close to its natural angle of repose with a slope of approximately 1 V:1 H (Abadi et al., 2018).

The influence of (ballast) shoulder profile was investigated by a number of authors over the last decade (Kabo, 2006; Le Pen, 2008). These studies generally agree that an increased shoulder width increases the lateral resistance of ballast. Abadi et al. (2018) studied the performance of shoulder slope (e.g. RPS to a slope of 1 V:2 H) on the settlement behaviour by carrying out tests in the SRTF apparatus. RPS showed the potential for reducing the required frequency of maintenance interventions by displaying smaller (36% reduction) and more uniformly distributed permanent settlements. This effect was linked with the improved lateral support provided to the ballast below the sleeper soffit by the shallower shoulder slope (Abadi et al., 2018). This is also consistent with Lackenby et al. (2007), who showed that increasing lateral confining stress resulted in a significant reduction in ballast settlement. Additionally, RPS modification exhibited improved behaviour in terms of higher stiffness, less movement of ballast on the shoulder slope, reduced breakage, and a reduction in the rate of development of the symptoms of centre binding (Abadi et al., 2018).

6.2.4 Results from SRTF

Key outputs of these tests are presented in Figure 6.3 to 6.5. Figure 6.3 shows that both types of interventions (e.g. USP and RFRs) have been successful in reducing the settlement throughout the cycles of each test over the base case for the tests using the first batch of Cliffe Hill ballast. The use of the soft USP shows the greatest improvement, next the stiff USP and finally the provision of RFRs ballast.

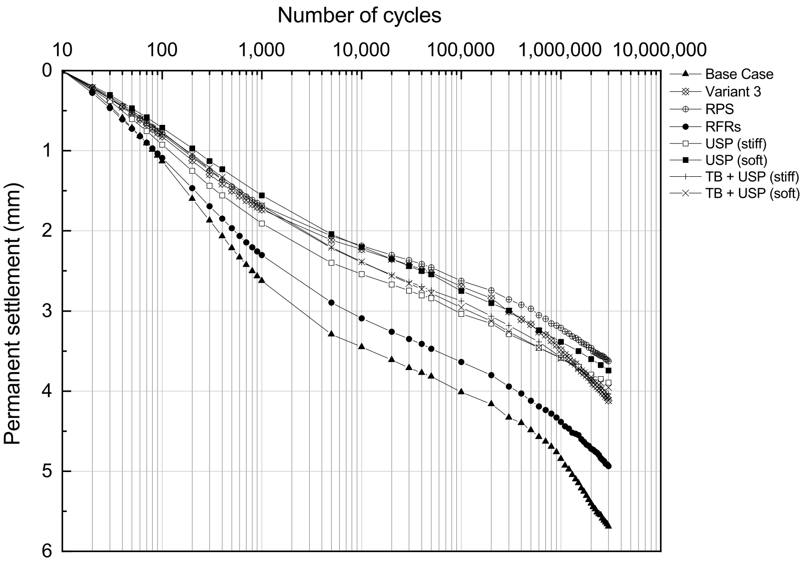


FIGURE 6.3: Settlement for railway track modifications compared with baseline case for Cliffe Hill first ballast tests.

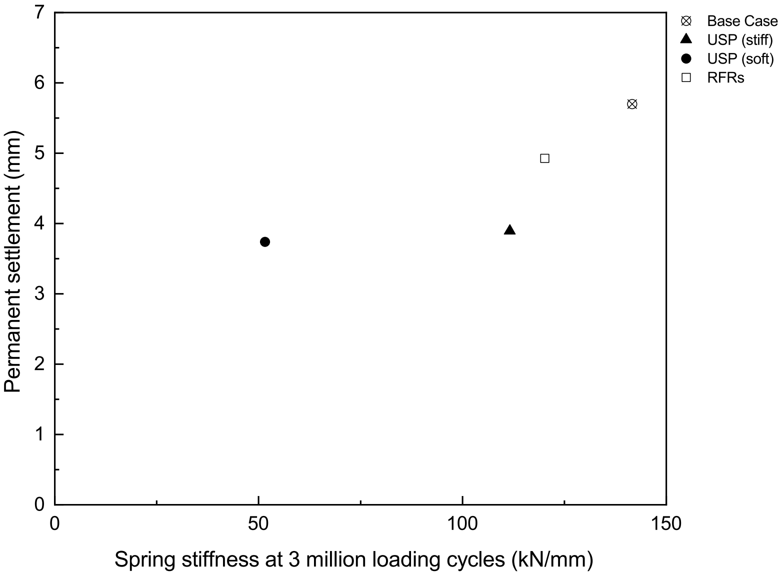


FIGURE 6.4: Spring stiffness against settlement for ballast modifications compared with baseline case.

Figure 6.4 shows the permanent settlement at 3 million cycles plotted against the spring stiffness. No strong trends are evident. However, further evaluation of stiffness Vs. settlement data by Abadi et al. (2018, 2019) considering other ballast and sleeper interventions showed that there was an inverse link between settlement and stiffness when the ballast type/gradation alone was the variable Figure 6.5.

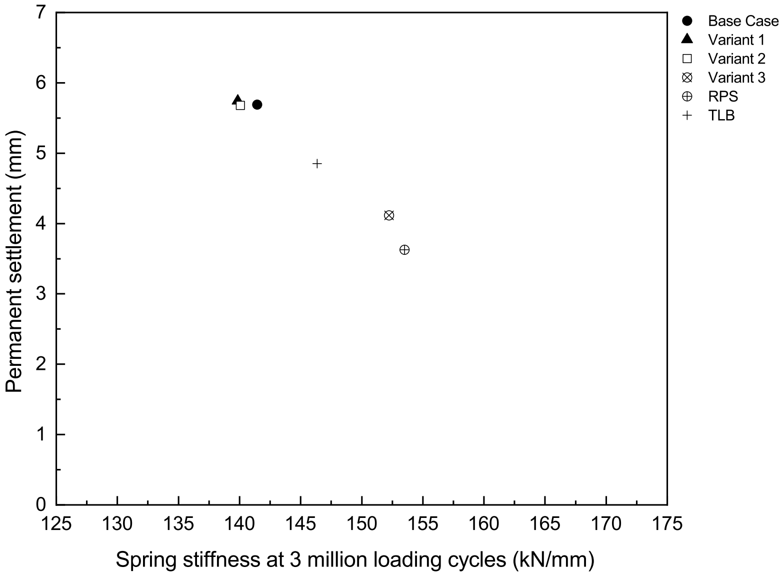


FIGURE 6.5: Spring stiffness against settlement for ballast modifications compared with baseline case.

In these tests however, non ballast materials have been introduced both into the ballast and onto the sleeper interface and this has altered the mechanisms of load transfer and stiffness behaviour. Thus, it may be concluded that the improvement in reducing settlement is not directly linked to the change in stiffness.

The lack of a clear link between stiffness and settlement in these tests precludes use of relative stiffness as a performance indicator. Therefore it is proposed to use the overall settlement as an indicator of differential settlement potential along an operating length of well performing railway track in which fouling is not a dominant factor. This proposed link requires further field study to fully validate. However, in the case of evaluating potential novel modifications where such field data does not yet readily exist (or where studies have been carried out they are not generalizable (Le Pen et al., 2018)), laboratory results can provide a basis for an approximation. The use of the average settlement to predict differential settlement has previously been observed to be reliable in other applications. Ricceri and Soranzo (1985) reported settlement measurements for a large number of structures built on different types of soil, finding a correlation between the maximum settlement (ρ_{max}) and the angular distortion ($\delta\rho/L$), where $\delta\rho$ is the relative settlement and L the distance between two consecutive points (Figure 6.6). Similarly, in railway engineering, the irregularities in the track geometry are expected to be proportional to the average settlement.

The angular distortion used by Ricceri and Soranzo (1985) indicates differential settlement. Figure 6.6 indicates a reasonably linear relationship exists between the maximum settlement

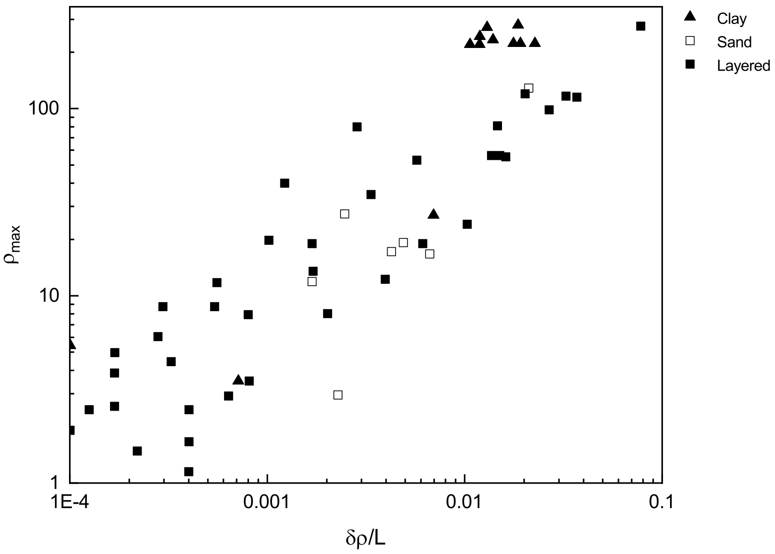


FIGURE 6.6: Correlation between the maximum settlement (ρ_{max}) and the angular distortion ($\delta\rho/L$) for structures on different foundation soil (reproduced after Ricceri and Soranzo (1985)).

and the angular distortion for a number of case studies and the classification of foundations by soil type also indicates that in general sand foundations are better performing than clay (as may have been expected).

6.2.5 Use of Laboratory tests to modify the LTSF

To relate the overall settlement shown for the tests in Figure 6.3 it is proposed to modify the LTSF (Equation 2.1) based on the relative proportions of settlement (Equation 6.1) while retaining the BCF as an unvaried effect (which could nevertheless be evaluated for influence in future work). For this study a linear correlation with a 1:1 constant of proportionality will be applied. To allow for a contribution from the subgrade to the differential settlement a further weighting is also applied allowing 80% to be due to the ballast and a further 20% for the subgrade (based on Figure 6.1 for a well performing subgrade). LTSF modifier values from this approach are shown in Table 6.2.

$$LTSF_{modifier} = \Delta_{currenttest}/\Delta_{baseline} \tag{6.1}$$

Table 6.2 applies an 80% weighting to the ballast settlement. However, where the subgrade is of poorer quality and/or has poor drainage this proportion could reduce to allow for increasing differential settlement from the subgrade soils present and further modifications to the approach could be needed should fouling be significant. The LTSF calculation for the RFRs ballast uses a different baseline value compared to the baseline value for the remaining modifications because of the different ballasts used.

TABLE 6.2: LTSF modifiers based on settlement at 3 million cycles.

Sleeper	Ballast	USP	Shoulder slope	Settlement at 3 million loading cycles δ (mm)	Ballast component of LTSF modifier	LTSF modifier assuming 80% due to ballast
Mono-block	NR[1]	None	1:1	5.69	1.00	1.00
Mono-block	NR[1]	USP (stiff)	1:1	3.89	0.68	0.75
Mono-block	NR[1]	USP (soft)	1:1	3.74	0.66	0.73
Twin-block	NR[1]	USP (stiff)	1:1	4.03	0.71	0.77
Twin-block	NR[1]	USP (soft)	1:1	3.96	0.70	0.76
Mono-block	V[1]	None	1:1	4.12	0.72	0.78
Mono-block	NR[1]	None	1:2	3.63	0.64	0.71
Mono-block	NR[2]	None	1:1	6.34	1.00	1.00
Mono-block	RFR Ballast[2]	None	1:1	4.85	0.76	0.81

[1] Cliffe Hill Batch 1.

[2] Cliffe Hill Batch 2.

6.2.6 Scope

This chapter critically appraises and compares the life cycle environmental impacts of installing novel interventions as standard at renewals on two different routes in the UK, the London – Portsmouth line and a section of the ECML between Newcastle and Edinburgh. For this analysis, a model has been developed to evaluate the carbon footprint of different modifications to ballasted track systems by adopting a lifecycle approach and the results are presented using a CO_2e metric.

The subsequent evaluated emissions have been normalised over a metre of double track ($t.CO_2e$ per metre of double track), to permit the summation of the environmental impacts of the different processes modelled within the examined lifecycle. The key processes included in this analysis are broken down in the three core phases of the infrastructure's life: construction, use (e.g. inspection, renewal, maintenance, etc.), and EoL, with the associated emissions being based on the devised table of EF (see Table 6.4). The methodology adopted in this work is based on the conceptual LCA framework guidelines designated by the ISO (2006a,b) and BSI (2016).

6.2.7 Inventory analysis and Functional Unit

The SB selected for the inventory analysis has been summarised in Figure 6.7, the shaded processes represent the upstream and downstream stages which are not scoped in the appraisal. It should be pointed out that the in scope activities, CFs, geographical coverage boundaries and track specifications adopted are chosen to represent the UK region.

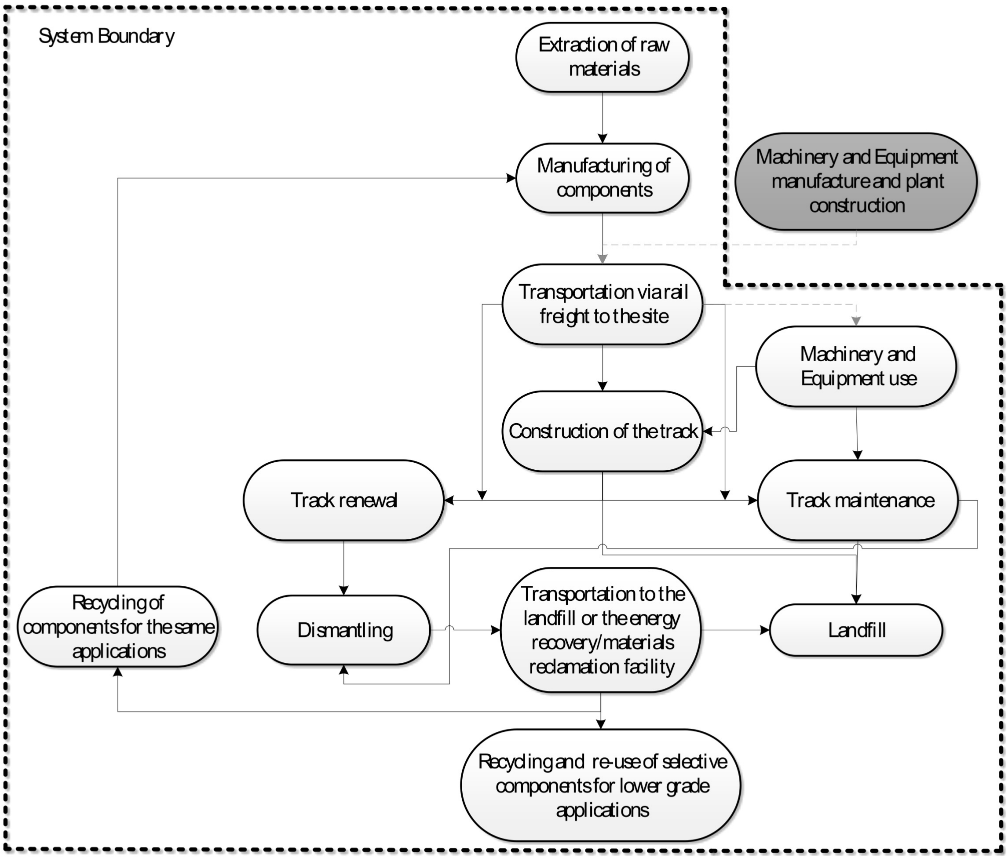


FIGURE 6.7: Simplified flow diagram and associated SB for the LCA carbon footprint model.

As already discussed, the environmental indicator metric of this appraisal is CO_2e, with the associated emissions being normalised over a metre of double railway track (dtm). Inventory data are converted to a FU of per 1.0 metre of double railway track.

Considering the lifecycle adopted for this study, a 60-year appraisal period (base year set by default as 2009) has been chosen in line with WebTAG recommendations (DfT, 2018), with the associated in scope processes being the raw material extraction, manufacturing of track components, transport on site via rail freight, infrastructure use (e.g. inspection, maintenance, renewal activities, etc.) including the dismantling of obsolete components and the subsequent relay/renewal of new ones and finally, the EoL phase of life-expired components following the appropriate downstream pathway.

6.2.7.1 Activity data Assumptions

Plain track Components

In order to carry out the appraisal, the following assumptions have been considered with respect to the plain track components used (Table 6.3).

TABLE 6.3: Railway track component activity data and assumptions. Sources: Abadi et al. (2018, 2019); Ferro (2018)

Component	Gradation/Slope	Description
UIC 60	n/a	Assumes two per (single) track
rail		Weight: 60 kg/m (per rail)
		Material: Steel (85% recycled content)
G44 Mono-block	n/a	Assumes sleeper spacing as 600-700 mm between centres
sleepers		Dimensions: 2500mm (l) 285mm (w) 210mm (h)
		Weight: 309 kg/sleeper
		Material: Concrete (1:2:4 Cement:Sand:Aggregate) and steel (virgin)
B450/U41 Twin-block	n/a	Assumes sleeper spacing as 600-700mm between centres
sleepers		Dimensions: 2415mm (l) 290mm (w) 220-260mm (h)
		Weight: 230 kg/sleeper
		Materials: Concrete (1:2:4 Cement:Sand:Aggregate) and steel (virgin)
Rail clips	n/a	Assumes two per rail, hence four per sleeper
		Weight: 0.75 kg/rail
		Material: Steel (85% recycled content)
Rail baseplates	n/a	Assumes two per sleeper
		Weight: 30 kg/baseplate
		Material: Steel (85% recycled content)
Rail pad	n/a	Assumes two per sleeper
		Weight: 0.51 kg/pad
		Material: Rubber
Ballast	NR/1:1	Assumes a ballast density of 1418 (loose) to 1625 (dense) kg/m^3
		Material: aggregate
	NR/1:2	Assumes a ballast density of 1418 (loose) to 1625 (dense) kg/m^3
		Material: aggregate
	V/1:1	Assumes a ballast density of 1512 (loose) to 1744 (dense) kg/m^3
		Material: aggregate
USP	n/a	Assumes 4mm (stiff) or 9mm (soft) pad per sleeper
		Weight: 2.6 kg/sleeper (stiff pad with G44 sleeper), 5.5 kg/sleeper (soft pad with G44 sleeper)
		Weight: 1.8 kg/sleeper (stiff pad with B450 sleeper), 3.8 kg/sleeper (soft pad with B450 sleeper)
		Material: Trackelast FC500 (stiff) and bonded cork (soft)
RFRs	NR/1:1	Assumes 1,637 fibres per metre of single track
		Weight: 0.00328 kg/fibre
		Material: Polyethylene

A summary of the plain track railway infrastructure LCI is shown in Table 6.4. This displays the material breakdown by mass and emission parameters (embodied, labour and plant, transport) calculated for each of the main track components based on the UK specifications.

6.2.8 Model construction

6.2.8.1 Embodied Emissions

The EC impact of the construction phase for each examined track component was estimated based on their material properties and carbon intensity values. The embodied CO_2e emissions, EC_j^{c-g} 'cradle-to-gate' associated with the manufacturing of each component were estimated by multiplying each material mass with the associated CF (Equation 6.2). These CFs are based on the Bath Inventory of Carbon and Energy (Hammond and Jones, 2011, 2019) and the RSSB's Rail Carbon Tool (RSSB, 2018).

$$EC_j^{c-g} = \sum_{i=1}^{n} M_i \times C_i \times CF_i \tag{6.2}$$

Where, EC_j^{c-g} is the aggregate embodied 'cradle-to-gate' $(c - g)$ CO_2e emissions for a track length of 1.0 metre laid with j component in $kgCO_2e/metre$; i is the material index; n is the total number of materials used in the construction of track component j; M_i is the mass of material i for each component given in kg per metre of single track; C_i is the % composition of each material to the total mass of the component; CF_i is the EC factor for each material i given in $kgCO_2e/kg$.

6.2.8.2 Component Processing

The labour and plant emissions arising during track installation have been estimated based on the machinery specifications (e.g. productivity) by Kiani et al. (2008) and the EFs by Ortega et al. (2018a), which were based on the Arup Group carbon database CO2ST (Arup, 2013). The calculation of these emissions has been made indirectly using the equation 6.3 shown below.

$$EC_{L-P_j}^{s} = \sum_{j,i=1}^{n} LT/M_{P_j} \times CF_{ji} \tag{6.3}$$

Where, $EC_{L-P_j}^{s}$ is the CO_2e emissions arising from the use of machinery and equipment for the construction, maintenance and relay/renewal on site in kg of CO_2e per FU selected; j is the machinery index; $i = 1, 2, 3, \ldots, n$ corresponding to a rated power of $100kW, 300kW, 400kW, \ldots, n$; n is the total number of equipment used in the installation of the railway component; LT is the length of track to be processed given in m; $M_{(P_j)}$ is the track-laying train productivity given in $m/hour$; CF_{ji} is the CF for machine j with engine size i given in $kgCO_2e/hour$ of combustion.

TABLE 6.4: Plain track railway infrastructure LCI.

Component	Sleeper	Gradation	Shoulder Slope	USP	CF	Mass of component	Embodied Emissions	Transport Emissions	Labour and Plant	Transport distance	Total
Units					*$kgCO_2e/kg$*	*kg per m*	*$kg\ CO_2e/m$*	*$kgCO_2e/m$ per km*	*$kg\ CO_2e/m$*	*km*	*$kg\ CO_2e/m$*
UIC 60					1.550	120.000	186.000	0.003	0.532	50.000	186.685
Sleeper	G44				0.256	362.560	92.924	0.009	0.152	50.000	93.539
	B450/U41				0.256	269.867	69.167	0.007	0.152	50.000	69.664
	W560H				1.460	87.413	127.623	0.002	0.152	50.000	127.887
	W400				1.460	80.021	116.831	0.002	0.152	50.000	117.085
Rail clips					2.270	1.760	3.995	0.000	0.000	0.000	3.997
Rail Baseplate					2.270	70.400	159.808	0.002	0.000	0.000	159.898
USP	G44			Stiff	2.850	3.087	8.797	0.000	0.000	0.000	8.801
				Soft	2.850	6.482	18.474	0.000	0.000	0.000	18.483
	B450/U41			Stiff	2.850	2.111	6.015	0.000	0.000	0.000	6.018
				Soft	2.850	4.432	12.633	0.000	0.000	0.000	12.638
Ballast		NR	1:1		0.005	2672.813	13.899	0.068	0.304	50.000	17.618
		Ballast variant	1:1		0.005	2868.545	14.916	0.073	0.304	50.000	18.886
		NR	1:2		0.005	3079.063	16.011	0.079	0.304	50.000	20.250
RFRs		NR	1:1		2.540	5.370	13.639	0.000	0.000	0.000	13.646
Rail Pad					2.850	1.020	2.907	0.000	0.000	0.000	2.908

TABLE 6.5: Machinery and equipment productivity per shift and associated CO_2e emissions per hour. Sources: Arup (2013)

Plant	Fuel Type	Plant Productivity $m/shift$	CF $kgCO_2e/hour$
Sleeper laying machine	Diesel	700.000	13.290
Rail laying machine	Diesel	200.000	13.290
Ballast spreading machine	Diesel	700.000	26.580
Tamping machine	Diesel	250.000	39.870

Dismantling of track components for each successive renewal has been also considered in this study. These emissions have been assigned to the use phase of the LCA instead of the EoL. This has been decided based on the capability of modern machinery to perform parallel dismantling and complete track bed renewal operation. Once again, the calculation of these emissions has been made indirectly using the equation 6.4.

For the case where complete track dismantling is necessary. These emissions can be calculated as follows:

$$EC_D^s = \sum_{j=1}^{n} EC_{L-Pj}^s \tag{6.4}$$

Where, EC_{L-Pj}^s is the CO_2e emissions arising from the use of machinery and equipment j for the dismantling of the track in kg of CO_2e per FU selected.

6.2.8.3 Component Transport Emissions

Emissions will also be produced from the transportation of components and materials associated with the construction, maintenance and/or renewal processes. Such emissions are highly 'site-specific', as they are dependent on the distance from the material source to the construction site, but also to the transport mode used. The CFs drawn from the RSSB's Rail Carbon Tool and Bath Inventory of Carbon and Energy (Hammond and Jones, 2011, 2019) are quoted as 'cradle-to-gate' rather than 'cradle-to-site' boundaries, and as these are average data (not a specific manufacturer), an arbitrary selected transport distance of 50 km has been chosen for all components, with the subsequent direct emissions assumed to arise via rail freight. Consequently, in order to evaluate the direct embodied emissions arising from the transportation of these components, the DBEIS rail freight 'all scope' EF (DBEIS, 2018) quoted in $kgCO_2e/kg\ km$ has been used (using equation 6.5).

$$EC_{Tj} = \sum_{j}\sum_{i}(M_{ji} \times T_{ji} \times CF_i) \tag{6.5}$$

Where, EC_{Tj} is the direct carbon emissions arising from the transportation of material, equipment and waste j expressed in kg of CO_2e per FU selected; M_{ji} is the amount of building material, component, equipment or waste j (in kg) to be transported by vehicle i; T_{ji} is the total transport distance for item j transported via vehicle i (in km); CF_i is the EF to transport an item using vehicle i (in $kgCO_2e/tonne \times km$).

6.2.8.4 Track Construction, Maintenance and Renewal

The total construction emissions for each component have been calculated using equation 6.6 shown below.

$$EC^s_{Cj} = EC_j^{c-g} + EC_{Tj} + EC^s_{L-Pj} \tag{6.6}$$

Where, EC_j^{c-g} is the aggregate embodied 'cradle-to-gate' ($c - g$) CO_2e emissions for a track length LT laid with component j in kg of CO_2e per FU selected; EC_{Tj} is the direct carbon emissions arising from the transport of materials, waste and equipment for the installation of component j expressed in kg of CO_2e per FU selected; EC^s_{L-Pj} is the CO_2e emissions arising from the labour and plant for component j on site in kg of CO_2e per FU selected.

Equation 6.6 can be rewritten to account for the construction of the entire track as follows:

$$EC^s_C = \sum_{j=1}^{n} EC^s_{Cj} \tag{6.7}$$

Where, EC^s_{Cj} is the aggregate construction emissions (e.g. embodied, transport, labour and plant) for component j in kg of CO_2e per FU.

The estimation of tamping emissions was made using equation 6.3 and the data from Table 6.5. For interventions with variable requirements (e.g. stoneblowing and rail grinding) the same proportion of emissions (2.73 and 6.54 times) with respect to tamping was assumed as did Milford and Allwood (2010). Traxcavation (i.e. ballast replacement using heavy excavation machinery) performance (and emissions) have been assumed to be identical to those of rail grinding and have been calculated using equation 6.8.

$$EC^s_R = EC^s_D + EC^s_C + EC^s_{Trax} + EC^s_{Tamp} \tag{6.8}$$

Where, EC^s_D is the CO_2e emissions arising from the use of machinery and equipment for the complete dismantling of the track on site in kg of CO_2e per FU selected (may be replaced by EC^s_{L-P}), EC^s_C is the total construction emissions (e.g. embodied, transport, labour and plant) for a defined length of track in kg of CO_2e per FU; EC^s_{Trax} and EC^s_{Tamp} are the CO_2e emissions arising from the traxcavation and tamping interventions in kg of CO_2e per FU.

Alternatively, when 'Resleeper Ballast Traxcavation' is selected instead of 'Complete Renewal and Traxcavation', the EC^s_C component of equation 6.8 will include only the emissions associated with the renewal of railway sleepers and ballast (and intervention where applicable) and exclude the emissions associated with the replacement of rails (and auxiliary equipment).

The calculation of the emissions from 'Single Rail Renewal' and 'Rerail' activities is made by using equation 6.7, where the EC^{s}_{Cj} component of the equation includes the following items: rails, rail clips, rail baseplate, and rail pad. Vertical and lateral rail repairs have been assumed to have identical emissions to those of a rail grinding machine, as the levels of rail repair will depend upon the amount of damage of particular rail sections, which means that an accurate estimation is not possible.

6.2.8.5 Track Inspection

Four different types of inspection have been considered in this study: geometry recording, ultrasonic test unit, visual inspection, and pedestrian ultrasonic. The geometry recording and ultrasonic test unit were assumed to be made at almost commercial operating speed (Arasteh Khouy et al., 2016). Therefore, it was assumed that they have the same emissions as a Class 165 diesel passenger train with two coaches. For the pedestrian ultrasonic testing and visual inspection, it was assumed that the inspection staff have to travel 50 km by rail on site, same distance as the rest of the interventions (e.g. materials, equipment, etc.), and their walking speed during inspection is around 1 to 2 km/hr, resulting to an approximate inspection volume of 10 km of single track per night shift.

6.2.8.6 S&C Renewal

In this model, the carbon impact of the complete renewal of S&Cs has been derived from the model presented in Chapter 5. Firstly, the impact of complete renewal of fifteen different design variants has been calculated and then normalised per metre of double track (see Table 6.6).

TABLE 6.6: LCI for S&C renewal. Units: $kg\ CO_2e$ per metre of double track.

Code	Switch size	Crossing angle	Layout	Complete renewal of S&C $kg \times CO_2e\ /\ m$
NR 56 v	BVs	8	Turnout	3027.532
	CVs	13	Turnout	2625.146
	CVs	13	Crossover	3253.924
	DVs	15	Turnout	2897.209
	DVs	15	Crossover	4026.828
NR 60 Mk1	C	11	Crossover	3870.772
	D	13.5	Crossover	2801.188
	E	17.25	Turnout	1831.976
	E	17.25	Crossover	3437.580
NR 60 Mk2	C	13	Turnout	2752.514
	C	13	Crossover	3773.865
	D	10.75	Turnout	3201.806
	D	15	Crossover	3305.374
	E	18.5	Crossover	2918.813
	E	21	Crossover	2529.011
mean			(μ)	3083.569
standard deviation			(σ)	569.585
upper bound				4026.828
lower bound				1831.976

Secondly, the mean (μ), standard deviation (σ), upper and lower bounds of the (normalised) impacts of renewals have been calculated (Table 6.6). These values serve as inputs to the route model, assuming that any additional intervention included will have a minor impact to the total footprint of S&Cs.

6.3 Results and Discussion

6.3.1 Simulated Scenarios

In total 16 programmed scenarios (eight for each route) have been tested (Table 6.7). These scenarios differentiate in terms of: (i) sleeper type (i.e. G44 mono-block or B450/U41 twin-block concrete sleepers), (ii) shoulder slope (either 1:1 or 1:2), (iii) ballast gradation (i.e. either traditional NR specification or ballast with finer gradation), (iv) installation of novel interventions (i.e. sleepers fitted with stiff or soft USP, or ballast with RFRs).

TABLE 6.7: Overview of simulated scenarios.

Label	Route	Sleeper Type	Shoulder Slope	Ballast Gradation	Intervention
1	ECML/Portsmouth Direct	G44	1:1	NR	no
2	ECML/Portsmouth Direct	G44	1:2	NR	no
3	ECML/Portsmouth Direct	G44	1:1	V	no
4	ECML/Portsmouth Direct	G44	1:1	NR	USP (stiff)
5	ECML/Portsmouth Direct	G44	1:1	NR	USP (soft)
6	ECML/Portsmouth Direct	G44	1:1	NR	RFRs
7	ECML/Portsmouth Direct	B450/U41	1:1	NR	USP (stiff)
8	ECML/Portsmouth Direct	B450/U41	1:1	NR	USP (soft)

The implications of these scenarios are analysed on two different routes in the UK: the London Waterloo to Portsmouth (Direct) line and a section of the ECML between Newcastle and Edinburgh. Both routes were developed in the 19th century, with the Newcastle – Edinburgh route used mainly by trains operating at high speed with an average EMGTPA of approximately 16. Speeds are generally lower on the London – Portsmouth route, with a high density of commuter traffic, and high service frequencies having an EMGTPA of approximately 22.

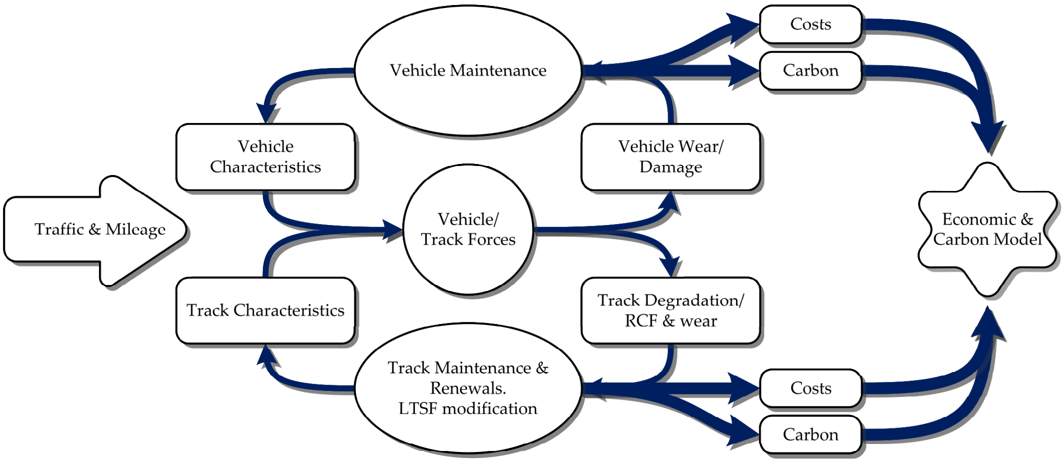


FIGURE 6.8: VTISM modelling framework (adapted after Rhodes et al. (2019)).

The track maintenance and renewals activity volumes were obtained using VTISM for both routes under these scenarios. The LTSF modifier was set for each scenario based on Table 6.2. Figure 6.8 provides a flow diagram for the VTISM analysis, including the input of the LTSF modifier (based on Table 6.2), and VTISM outputs giving the volume of all interventions over the project life. The LTSF modifier is included at each track renewal (shown at the bottom of Figure 6.8).

6.3.2 LCA Modelling Results

6.3.2.1 Carbon Footprint Results : Cradle-to-Grave

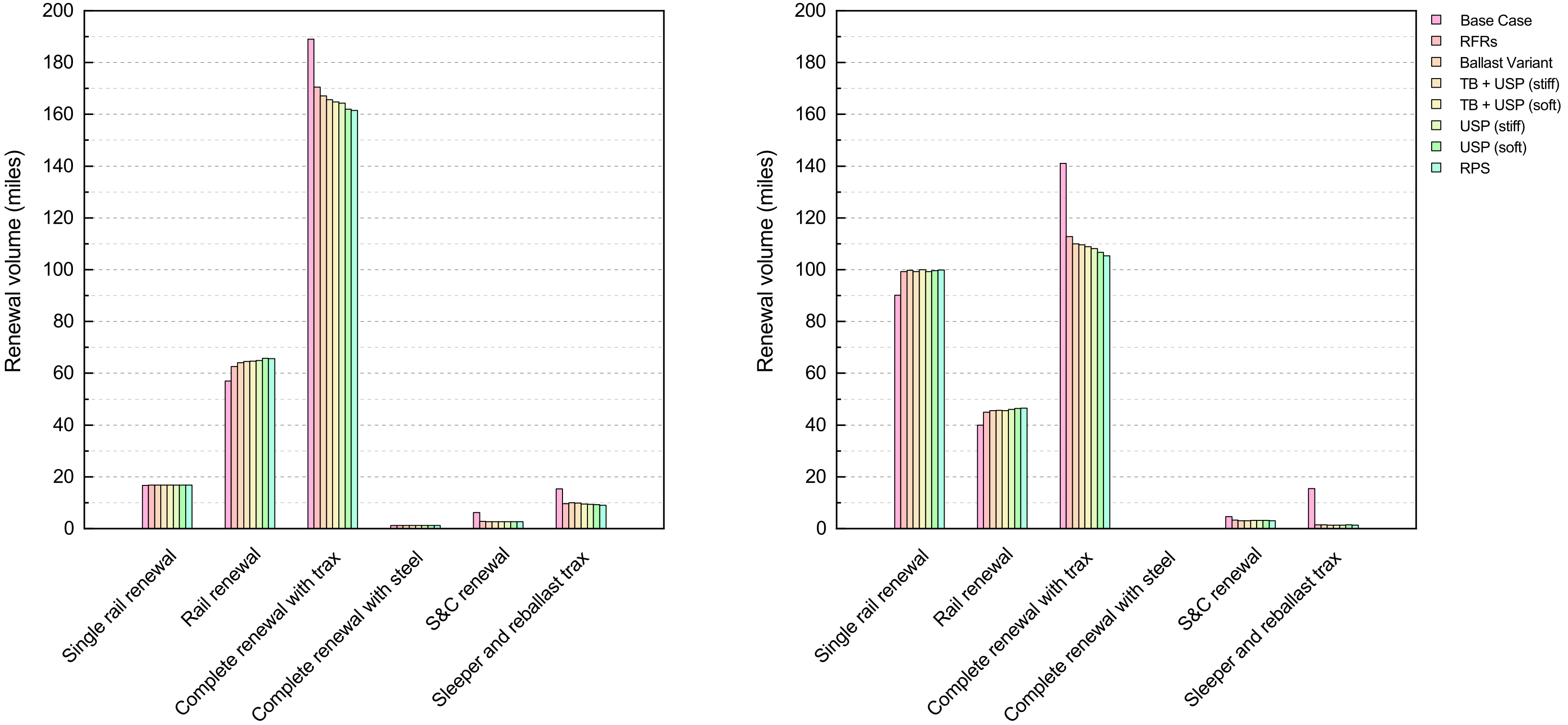
VTISM outputs the volume of works which are undertaken to the track system for the whole section under consideration after 60 years as aggregate miles for each renewal and maintenance intervention as well as on a per mile basis. Annual volumes of work were also obtained from each simulation for further analysis (Figure 6.9 and 6.10). These intervention volumes (maintenance, renewal and inspection) were converted from miles to metres and multiplied by their respective emission parameter. A summary of the calculated carbon emissions inventory for each work activity is shown in Table 6.8.

Following the installation of each intervention, the performance improvement on the rail track is reflected from the reduced volume of annual renewal (Figure 6.9) and maintenance (Figure 6.10) actions. It is expected that emission savings from the newly introduced interventions will also arise through the reduction of these actions on the railway route. However, it is anticipated that the positive benefits will occur over time as the additional materials will initially increase the embedded carbon of the infrastructure. Inspection actions will have no contribution to these benefits as their annual volumes are identical across all scenarios. According to VTISM, on the ECML route there would be some renewal of steel sleepers, but as the volumes involved were negligible and identical for all scenarios, these were omitted from the analysis. However, for illustrative purposes, a calculation of these emissions was performed assuming the use of either W560H or W400 steel sleepers. It has been found that these emissions account for less than 0.05% of the total footprint of the route.

In the base year approximately 7% of the stretch between Newcastle to Edinburgh and 13% of that of London Waterloo to Portsmouth would be renewed with traxcavation. For projected calculations, it was assumed that interventions can be installed at each successive renewal where sleepers and ballast are installed. It is estimated that after 60 years approximately 71 to 75%, of the track will have the newly introduced track modifications installed for the ECML. Similarly, around 74 to 79% of the track will be installed with these modifications for the Portsmouth (Direct) Line.

TABLE 6.8: LCI for each work activity. Units: $kg\ CO_2e$ per metre of double track.

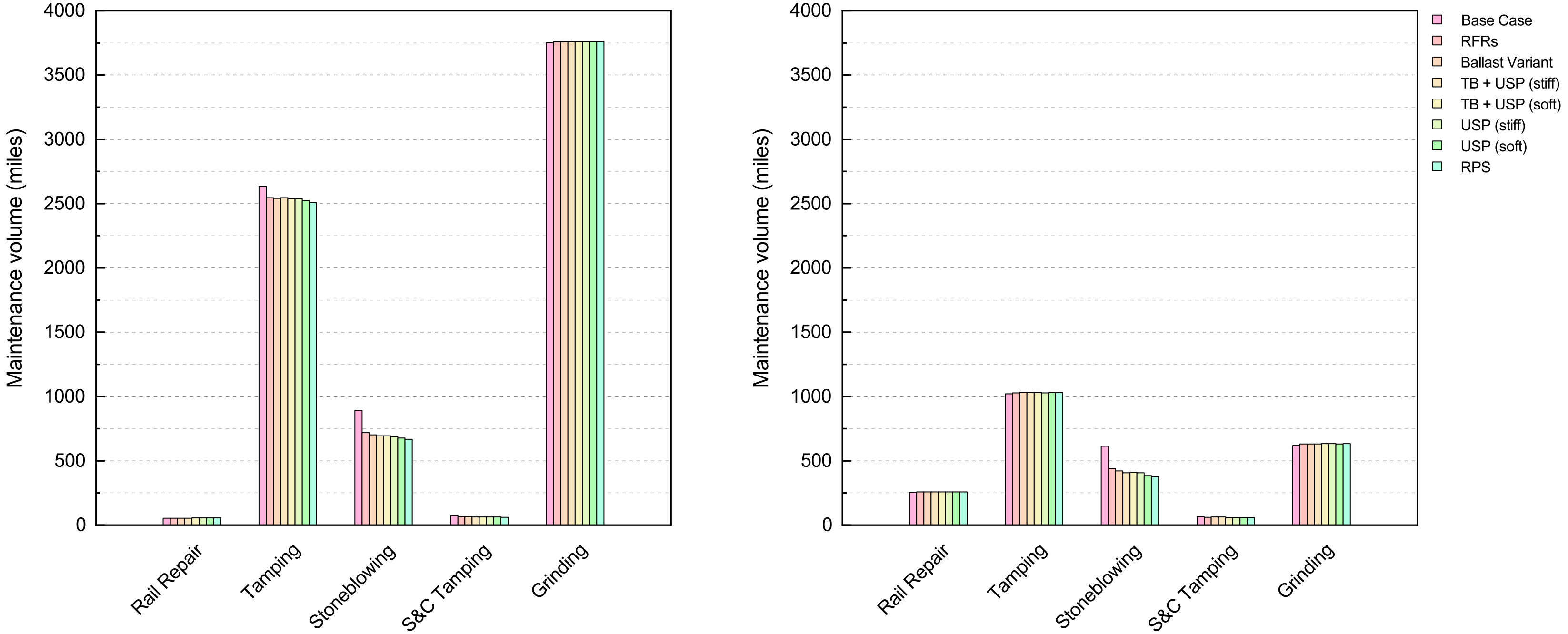
Work Description		Boundary	Base case	Ballast variant	USP (stiff)	USP (soft)	TB + USP (stiff)	TB + USP (soft)	RFRs	RPS
Renewal	Complete Renewal & Traxcavation	A1-5 + B4-5 + C1	958.502	961.038	976.104	995.467	922.787	936.027	985.793	963.765
	ReSleeper Ballast Traxcavation	A1-5 + B4-5 + C1	244.593	247.129	262.195	281.558	208.877	222.117	271.884	249.856
	Rerail	A1-5 + B4-5 + C1	714.972	714.972	714.972	714.972	714.972	714.972	714.972	714.972
	S&C Renewal	A1-5 + B4-5 + C1	3083.569	3083.569	3083.569	3083.569	3083.569	3083.569	3083.569	3083.569
	Complete Renewal with Steel	A1-5 + B4-5 + C1	255.774	255.774	255.774	255.774	255.774	255.774	255.774	255.774
Renewal & Maintenance	Single rail renewal	A1-5 + B4-5 + C1	178.743	178. 743	178. 743	178. 743	178. 743	178. 743	178. 743	178. 743
Maintenance	Rail Repair (Lateral + Vertical)	B2-3	16.688	16.688	16.688	16.688	16.688	16.688	16.688	16.688
	Tamping	B2-3	2.552	2.552	2.552	2.552	2.552	2.552	2.552	2.552
	Stoneblowing	B2-3	6.966	6.966	6.966	6.966	6.966	6.966	6.966	6.966
	S&C Tamping	B2-3	5.103	5.103	5.103	5.103	5.103	5.103	5.103	5.103
	Rail Grinding	B2-3	16.688	16.688	16.688	16.688	16.688	16.688	16.688	16.688
Inspection	Visual inspection	B2	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Geometry recording	B2	3.648	3.648	3.648	3.648	3.648	3.648	3.648	3.648
	Ultrasonic test unit	B2	3.648	3.648	3.648	3.648	3.648	3.648	3.648	3.648
	Pedestrian Ultrasonic	B2	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002



(A) ECML

(B) Portsmouth (Direct) Line

FIGURE 6.9: Total volume of renewal actions for each route.



(A) ECML

(B) Portsmouth (Direct) Line

FIGURE 6.10: Total volume of maintenance actions for each route.

A summary of the aggregate CO_2e emissions per type of work over the whole simulated period for both the ECML and the Portsmouth (Direct) Line is shown in Table 6.9 and 6.10. Some initial conclusions that can be drawn from these Tables are with respect to the magnitude of improvement from the inclusion of these interventions. These improvements appear to be relatively small compared to the overall footprint for each route (i.e. 3.0 to 5.2% for the ECML and 7.1 to 10.1% for the Portsmouth line).

For both routes, the main benefits arise from the reduction in the use of carbon intensive materials (e.g. steel, concrete, etc.). This results from the reduction in the volume of complete renewals with traxcavation and sleeper and ballast renewals (Figure 6.9). Additionally, although there is a minor increase in tamping volumes for these routes, both stoneblowing and S&C renewals are reduced, translating to considerable relative savings compared to other work activities (Figure 6.11 and 6.12).

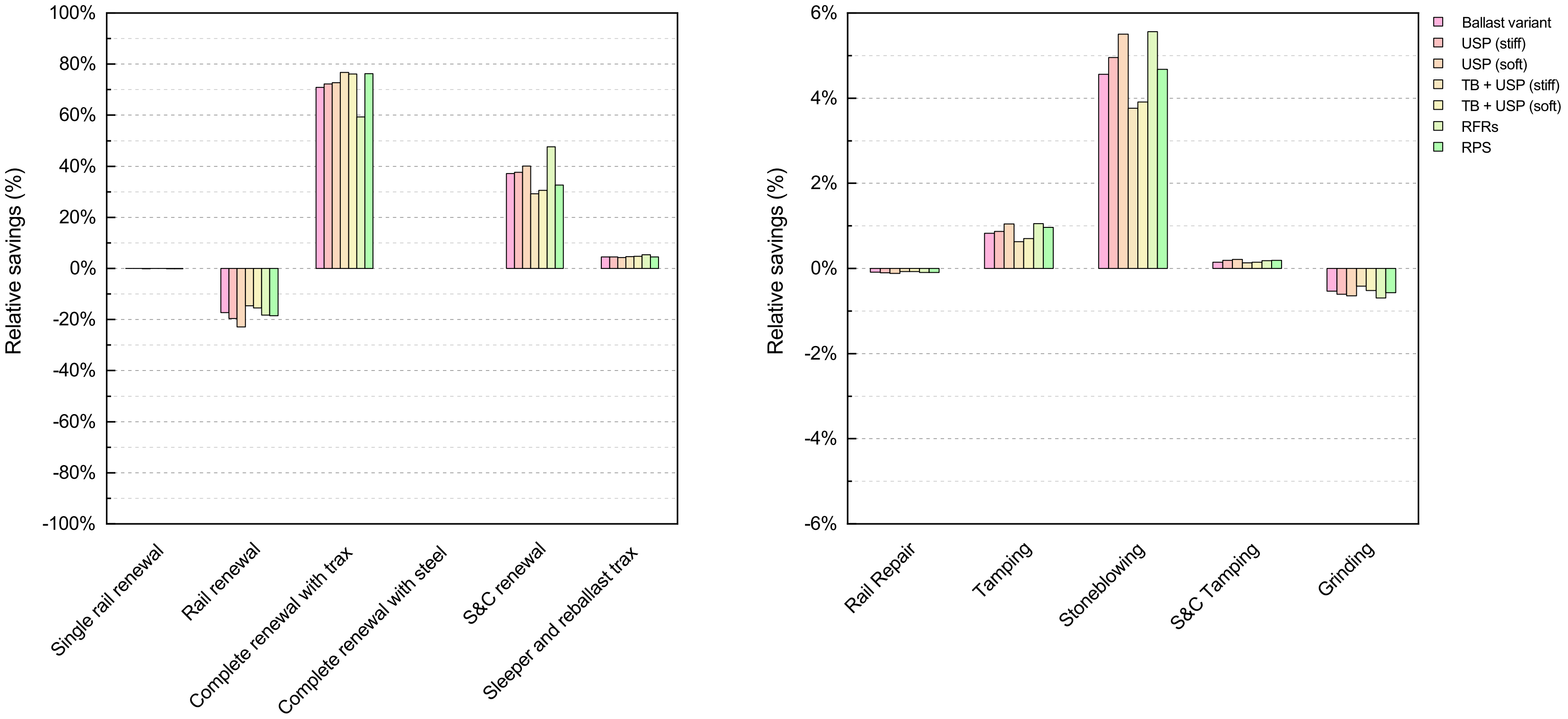
In detail, the reductions in the volume of complete renewals with traxcavation (Figure 6.9), resulted to an aggregate GHG emissions reduction of between 10,465 to 22,742 tonnes of CO_2e for the ECML and 19,336 to 27,435 tonnes of CO_2e for the Portsmouth line. Similarly, the reductions in the volume of sleeper and ballast renewals (Figure 6.9) led to a decrease in GHG emissions of around 928 to 1,375 tonnes of CO_2e for the ECML and 2,705 to 2,806 tonnes of CO_2e for the Portsmouth line. Likewise, the newly introduced interventions resulted to some important reductions in the volume of S&C renewals, which translated to a decrease of the total GHG emissions of these activities by about 8,399 to 8,774 for the ECML and 3,394 to 3,992 tonnes of CO_2e for the Portsmouth line. Conversely, there was an evident increase in the volumes of single and complete rail renewals (Figure 6.9) for both routes. These increases resulted to a growth in the lifecycle emissions by 3,230 to 5,046 tonnes of CO_2e for the ECML and 4,194 to 5,223 tonnes of CO_2e for the Portsmouth line.

TABLE 6.9: Summary of carbon footprint for each scenario for the ECML. Units: tonnes of CO_2e.

Work Description		Boundary	Base case	Ballast variant	USP (stiff)	USP (soft)	TB + USP (stiff)	TB + USP (soft)	RFRs	RPS
Renewal	Complete Renewal & Traxcavation	A1-5 + B4-5 + C1	145,766	129,242	129,031	129,810	123,024	124,165	135,301	125,265
	ReSleeper Ballast Traxcavation	A1-5 + B4-5 + C1	3,028	1,980	1,991	2,100	1,653	1,692	2,093	1,803
	Rerail	A1-5 + B4-5 + C1	32,797	36,845	37,351	37,829	37,142	37,191	36,011	37,765
	S&C Renewal	A1-5 + B4-5 + C1	15,277	6,610	6,558	6,503	6,610	6,610	6,878	6,503
	Complete Renewal with Steel	A1-5 + B4-5 + C1	239	239	239	239	239	239	239	239
Renewal & Maintenance	Single rail renewal	A1-5 + B4-5 + C1	2,407	2,421	2,420	2,421	2,420	2,421	2,423	2,424
Maintenance	Rail Repair (Lateral + Vertical)	B2-3	715	735	738	740	736	736	732	740
	Tamping	B2-3	5,412	5,219	5,211	5,183	5,225	5,213	5,227	5,152
	Stoneblowing	B2-3	5,003	3,939	3,855	3,797	3,889	3,894	4,022	3,745
	S&C Tamping	B2-3	303	269	259	256	265	261	271	252
	Rail Grinding	B2-3	50,363	50,488	50,503	50,504	50,487	50,511	50,485	50,516
Inspection	Visual inspection	B2	566	566	566	566	566	566	566	566
	Geometry recording	B2	223,586	223,586	223,586	223,586	223,586	223,586	223,586	223,586
	Ultrasonic test unit	B2	111,793	111,793	111,793	111,793	111,793	111,793	111,793	111,793
	Pedestrian Ultrasonic	B2	19	19	19	19	19	19	19	19
Total Footprint			597,275	573,951	574,119	575,347	567,654	568,898	579,646	570,369
Carbon Savings			n/a	23,324	23,156	21,928	29,621	28,377	17,629	26,906
			n/a	4.1%	4.0%	3.8%	5.2%	5.0%	3.0%	4.7%
Carbon Cost Savings (£k)			n/a	2,459.462	2,373.776	2,160.643	3,261.888	3,068.493	1,771.951	2,819.147

TABLE 6.10: Summary of carbon footprint for each scenario for the Portsmouth (Direct) Line. Units: tonnes of CO_2e.

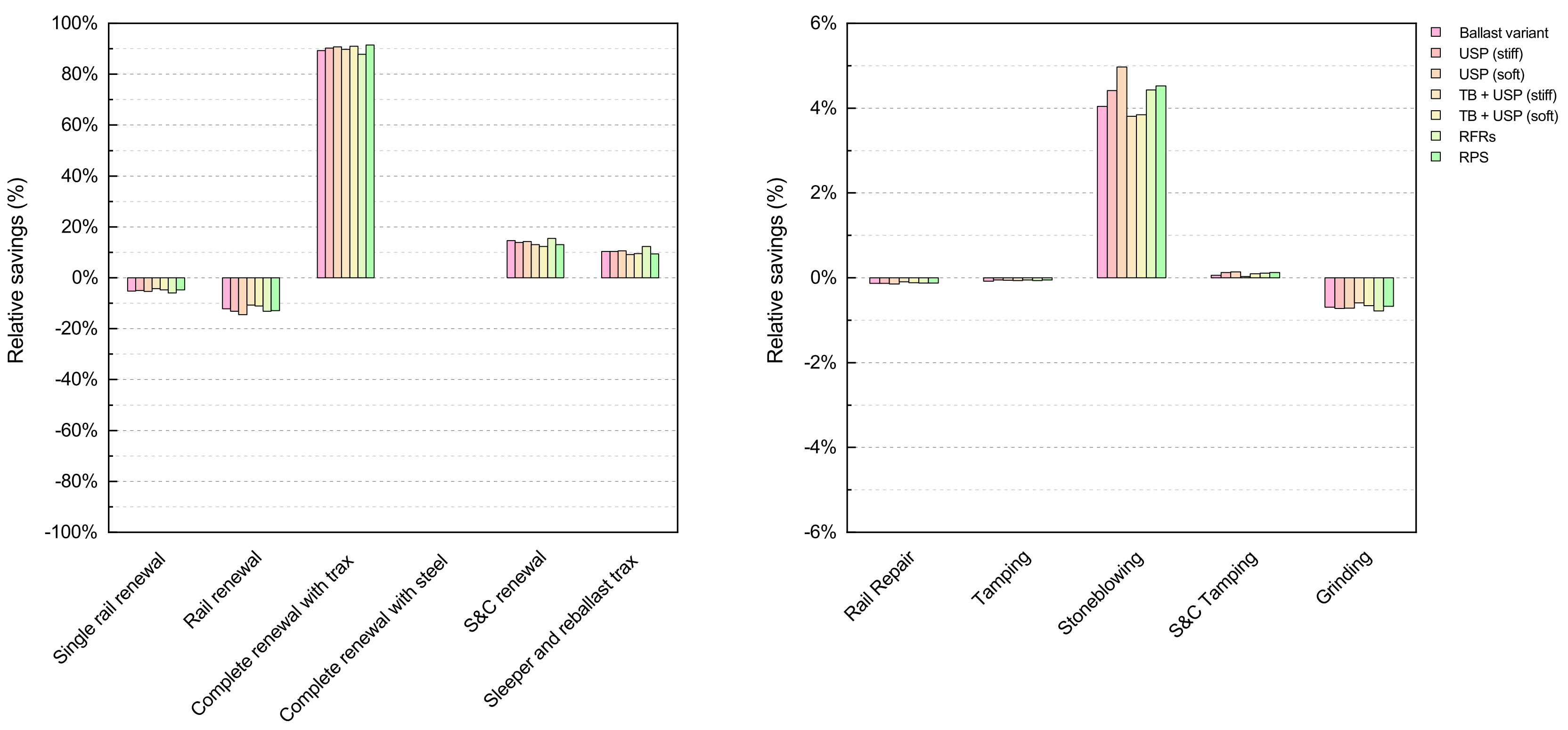
Work Description		Boundary	Base case	Ballast variant	USP (stiff)	USP (soft)	TB + USP (stiff)	TB + USP (soft)	RFRs	RPS
Renewal	Complete Renewal & Traxcavation	A1-5 + B4-5 + C1	108,813	85,095	84,972	85,442	81,378	82,032	89,477	81,742
	ReSleeper Ballast Traxcavation	A1-5 + B4-5 + C1	3,036	296	287	318	230	244	331	273
	Rerail	A1-5 + B4-5 + C1	22,969	26,214	26,458	26,689	26,264	26,231	25,855	26,801
	S&C Renewal	A1-5 + B4-5 + C1	11,404	7,516	7,727	7,727	7,412	7,784	8,010	7,533
	Complete Renewal with Steel	A1-5 + B4-5 + C1	0	0	0	0	0	0	0	0
Renewal & Maintenance	Single rail renewal	A1-5 + B4-5 + C1	12,972	14,348	14,278	14,338	14,285	14,382	14,280	14,363
Maintenance	Rail Repair (Lateral + Vertical)	B2-3	3,442	3,476	3,476	3,480	3,471	3,477	3,469	3,479
	Tamping	B2-3	2,098	2,119	2,112	2,113	2,119	2,114	2,113	2,114
	Stoneblowing	B2-3	3,442	2,367	2,275	2,162	2,277	2,311	2,467	2,103
	S&C Tamping	B2-3	273	257	241	238	263	244	249	237
	Rail Grinding	B2-3	8,304	8,488	8,496	8,488	8,486	8,498	8,476	8,504
Inspection	Visual inspection	B2	340	340	340	340	340	340	340	340
	Geometry recording	B2	104,004	104,004	104,004	104,004	104,004	104,004	104,004	104,004
	Ultrasonic test unit	B2	52,194	52,194	52,194	52,194	52,194	52,194	52,194	52,194
	Pedestrian Ultrasonic	B2	9	9	9	9	9	9	9	9
Total Footprint			333,298	306,722	306,869	307,542	302,730	303,862	311,273	303,695
Carbon Savings			n/a	26,576	26,429	25,756	30,568	29,436	22,025	29,603
			n/a	8.7%	8.6%	8.4%	10.1%	9.7%	7.1%	9.7%
Carbon Cost Savings (£k)			n/a	2,915.344	2,868.889	2,745.164	3,449.379	3,305.112	2,360.294	3,244.422



(A) Renewal works

(B) Maintenance works

FIGURE 6.11: Relative savings (%) for renewal and maintenance actions. ECML



(A) Renewal works

(B) Maintenance works

FIGURE 6.12: Relative savings (%) for renewal and maintenance actions. Portsmouth (Direct) Line.

To form a clearer view of the improvement offered by these modifications, the total emissions (i.e. maintenance and renewal) expressed in tonnes of CO_2e per year have been plotted in terms of cumulative difference over time normalised with respect to the base case (Figure 6.13).

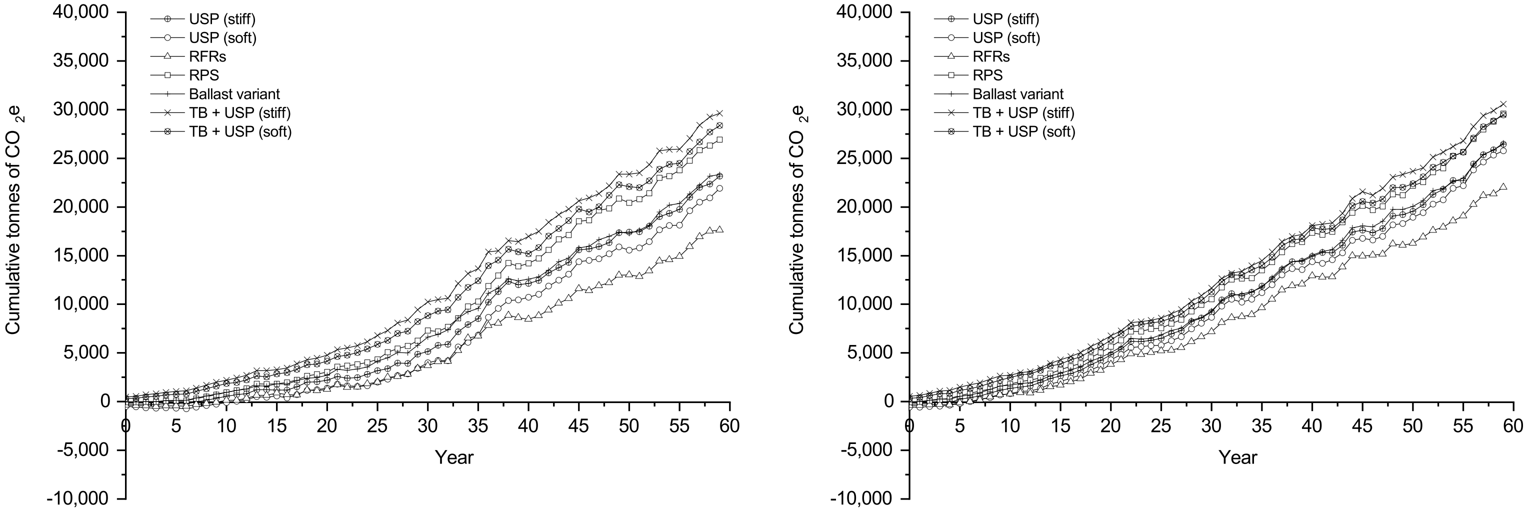
This revealed that for the ECML the breakeven point is achieved after between eight to eleven years after the first installation of stiff or soft USPs. Considering the impacts of RFRs on the same route, their carbon balance will start being positive ten years from the first installation. Conversely, for softer track modifications such as those of the shoulder slope and ballast gradation, the carbon impacts offset considerably faster (between two to four years from the first installation). Similarly, the replacement of mono-block with twin-block sleepers (with USPs) results in the carbon impacts to become positive right after the first installation, due to their lower embodied carbon (Table 6.4) per metre of double track installed (Table 6.8).

Considering the inclusion of stiff USPs on the Portsmouth line, the break-even point will be now achieved three years earlier than the equivalent installation on the ECML. Similarly, the carbon benefits from both soft USPs and RFRs will occur seven years from their first installation (four to five years earlier than their equivalent installations on the ECML). Once again softer modifications result in a positive footprint early on the appraisal period (e.g. two to three years). This suggests that if justified from a financial viewpoint, these interventions should be preferred.

6.3.2.2 Carbon Footprint Costs

Once the GHG emissions resulting from each scenario have been quantified, these are given a monetary value. Considering this, the carbon values (in 2021 prices) given by the DfT (2022) are used to monetise the changes in emissions from each option. For these calculations, similarly to the case studies presented in Chapter 4 and 5, the base test discount rate was taken as 3.5% for the first 30 years of the appraisal and a lower discount rate of 3.0% was used thereafter (as recommended by HM Treasury (2018)).

This analysis (see Table 6.9 and 6.10) revealed that the use of twin-block concrete sleepers (with USP), instead of mono-block can bring about a benefit of £3.068 (soft USP) to £3.261 million (stiff USP) for the ECML and £3.305 (soft USP) to £3.449 million (stiff USP) for the Portsmouth line. Softer track modifications can bring about a benefit of £2.459 to £2.819 million and £2.915 to £3.244 million for the ECML and Portsmouth line, respectively. Of which the higher reported (carbon cost) benefits (regardless of route) correspond to the installation of RPS ballasted track. Similarly, the inclusion of stiff or soft USP results in similar benefits of approximately £2.160 (soft USP) to £2.373 million (stiff USP) for the ECML and £2.745 to £2.868 million for the Portsmouth line. Finally, the installation of RFRs (regardless of route) results in a welfare benefit of approximately £1.771 to £2.360 million, which is the lowest expected across all of the examined options.



(A) ECML.

(B) Portsmouth (Direct) Line.

FIGURE 6.13: Cumulative tonnes of CO_2e over time.

6.3.3 LCCA Modelling Formulation

6.3.3.1 Net Present Value

The annual undiscounted cost for each work action (e.g. maintenance, renewal, inspection) was estimated based on their annual volume and unit cost values. These were calculated by multiplying the annual volumes of work for each action with the associated unit cost (Equation 6.9).

$$C_{it} = V_{it} \times C_i \tag{6.9}$$

Where, C_{it} is the annual cost of work action i in year t; V_{it} is the work volume of action i in year t; and C_i is the unit cost of work action i.

Equation 6.9 can be rewritten to account for the additional annual cost from the installation of each intervention:

$$C_{it}^{j} = V_{it} \times (C_i + C_j) \tag{6.10}$$

Where, C_{it}^{j} is the total annual undiscounted cost of work action i in year t (including the additional cost for intervention j); V_{it} is the work volume of action i in year t; C_i is the unit cost of work action i ('Complete Renewal and Traxcavation', 'ReSleeper Ballast Traxcavation', and 'S&C renewal'); C_j is the unit cost of intervention j.

Then the total annual undiscounted cost for the renewal of the track with the newly introduced interventions (C_t^j) can be calculated using equation 6.11.

$$C_t^j = \sum_{i=1}^{n=3} C_{it}^{j} \tag{6.11}$$

Similarly, the annual undiscounted costs from the remaining work actions are summed to calculate the total annual cash flows (C_t) using equation 6.12.

$$C_t = \sum_{i=1}^{n} C_{it} \tag{6.12}$$

The total discounted costs were then estimated for the first 30 years of the appraisal using equation 6.13.

$$TC_{n_1}^{j} = \sum_{t=0}^{n_1=30} \frac{C_t + C_t^j}{(1+d_1)^t} \tag{6.13}$$

Where, $TC_{n_1}^{j}$ is the total LCC with intervention j in present value for the first 30 years of the appraisal; C_t^j is the sum of relevant annual renewal costs with intervention j; C_t is the sum of the remaining annual renewal, maintenance and inspection costs; n_1 is the number of years in (i.e. 0 to 30 years); d_1 is the discount rate for the first 30 years of the appraisal (i.e. 3.5%).

Then the total discounted costs for the next 30 year period were calculated using equation 6.14.

$$TC^j_{n_2} = \sum_{t=31}^{n_2=60} \frac{C_t + C^j_t}{(1+d_1)^{n_1} \times (1+d_2)^{t-n_1}} \tag{6.14}$$

Where, $TC^j_{n_2}$ is the total LCC with intervention j in present value for the last 30 years of the appraisal; C^j_t is the sum of relevant annual renewal costs with intervention j; C_t is the sum of the remaining annual renewal, maintenance and inspection costs; n_2 is the number of years (31 to 60 years); d_1 is the discount rate for the first 30 years of the appraisal (i.e. 3.5%); d_2 is the discount rate for the last 30 years of the appraisal (i.e. 3.0%).

The total LCC with intervention j in present value for the whole appraisal period can then be calculated by summing the outputs from equations 6.13 and 6.14.

$$TC^j = TC^j_{n_1} + TC^j_{n_2} \tag{6.15}$$

The same procedure is carried out for calculating the total present value LCC (TC^b) for the base case, but the (C^j_t) component of the cost function will now be omitted. The difference between these cost components is equal to the NPV for each intervention option j.

$$NPV = TC^b - TC^j \tag{6.16}$$

6.3.3.2 Internal Rate of Return

As an alternative to the NPV, the IRR is introduced for optioneering of different track interventions. This is defined for each scenario as the rate at which the NPV is equal to zero, this is calculated by using the equation 6.17.

$$\sum_{t=0}^{n=60} \frac{C^b_t - (C_t + C^j_t)}{(1+d)^t} = 0 \tag{6.17}$$

Under this decision criterion, an option should be undertaken, if d is greater or equal to the test discount rate for the project. The test discount rate is linked to the opportunity cost of capital invested, thus, any infrastructure investment to be accepted, should generate a return (at least) equal to that elsewhere in the capital market (Boussabaine and Kirkham, 2004).

It is worth noting that this criterion is often prone to errors and problems, such as for example, the presence of multiple roots, or the provision of inconsistent rankings, when comparing mutually exclusive projects (Layard and Glaister, 1994).

6.3.3.3 Payback Period

The payback period may be defined as the period of time elapsed from the onset of a project investment until the point on its service life, where its cumulative cash flows start being positive (Boussabaine and Kirkham, 2004).

6.3.4 LCCA Modelling Results

In this section the cost implications are analysed after installing each intervention during renewals on two different routes in the UK. The track maintenance and renewals volumes were obtained using VTISM for both routes under eight scenarios (Table 6.7), covering a base case and the separate installation of seven modification to the conventional ballasted track. For these calculations the base year for discounting is 2009 (default year for our version of VTISM), with the base test discount rate taken as 3.5% for the first 30 years, and a lower discount rate of 3.0% used thereafter.

After the installation of these interventions, the main benefits were expected to arise from an increased service life of the track and a reduced maintenance and renewal volume, which would also lead to less disruption to scheduled train services. A renewal with traxcavation in the first year of 13% of the London – Portsmouth route is assumed by VTISM and the rails would be replaced for around 5 miles. The corresponding figures for the ECML would be 6% of the route and around 10 miles respectively. About 1 – 1.5% of each route would be traxcavated and renewed in each of the remaining years of the period. The replacement and maintenance regimes are not identical due to different scheduled interventions, which are given by actions from NR's renewal and maintenance budgets. Some parts of the track would for example only need rail renewals because ballast would be in an acceptable state, whilst other stretches would require a full renewal with traxcavation.

The cost of each renewal activity that implies removing ballast and lifting the track will be increased by £74,280/mile (£92,920 in 2021 prices) of double track in the USP (stiff or soft) scenario and £52,033/mile (£65,090 in 2021 prices) of double track in the RFRs scenario. Similarly, for soft track modification such as those of shallower shoulder slope and finer ballast gradation, the additional cost of each renewal activity will be driven by the additional amount of ballast required for each case. These modifications will increase the cost per mile of double track by £13,889 (Ballast variant: £17,374 in 2021 prices) and £28,828 (RPS: £36,062 in 2021 prices). For the case of replacing the existing mono-block sleepers with twin-block sleepers with USP, due to the lack of available unit cost data for the latter, it was assumed that both sleepers have identical unit costs and the only additional cost will be that of the USPs. These additional costs will only apply to complete renewal and traxcavation, re-sleeper ballast and traxcavation and finally, S&C renewals. For instance, in the first year the cost of installing RFRs on the Portsmouth line would be almost £475,000 while the corresponding cost of installing USPs would be £720,000.

After installing each intervention at renewals the LTSF is modified and this is reflected in the subsequent maintenance and renewal volumes. Figure 6.9 and 6.10 show the renewal and maintenance volumes under all eight scenarios for both study routes over the project life. It can be anticipated that the main cost savings from the new policy arise from changes in the renewal and maintenance needs. Inspection volumes are identical in both route scenarios so are not shown in these figures and therefore will have no influence on the savings.

Several conclusions can be drawn from Figure 6.9 and 6.10. Firstly, when installing these interventions, the maintenance and renewal frequencies are decreased. In other words, using these interventions at renewal is a good strategy to reduce material and energy needs and therefore costs. The installation of RPS track (lowest LTSF modifier) reduced these needs more than the installation of any other intervention. Similarly, the inclusion of USPs (regardless of stiffness) reduced these needs more than the installation of RFRs (with a slightly higher LTSF modifier). Secondly, the main benefit arises from the complete renewal with traxcavation, whereas the main disbenefit comes from more rail renewal needs and therefore higher cost. Thirdly, with respect to maintenance the main benefit comes from the reduction of stoneblowing needs, but tamping, rail grinding and repair needs might be increased. Finally, the maintenance and renewal difference between both routes is mainly explained by traffic conditions; on the London -– Portsmouth route there is more traffic than on the ECML and therefore all components degrade faster.

Table 6.11 and 6.12 show the aggregated discounted costs over the 60-year lifecycle per type of intervention for each route. Based on these results, the following points can be drawn. First, with respect to the aggregate figures, costs are reduced regardless of the choice of modification for both routes. The total average savings account for about 10.6 to 13.6% of the LCC for the ECML and 9.7 to 12.5% for the Portsmouth line. In detail (see Table 6.11 and 6.12), these savings represent 11.6% (USP stiff), 12.1% (USP soft), 10.6% (RFRs), 13.6% (RPS), 12.4% (Ballast variant), or 11.1 to 11.4% (Twin-block sleepers with USPs) of the LCC for the Newcastle – Edinburgh route and 10.7% (USP stiff), 11.1% (USP soft), 9.7% (RFRs), 12.5% (RPS), 11.2% (Ballast variant), or 10.4 to 10.5% (Twin-block sleepers with USPs) of the LCC for the Portsmouth line. Therefore, the IM should choose between renewals over the basis of additional expected benefits of each intervention, since cost savings are quite similar for all interventions.

Second, as expected, the installation of USPs (stiff or soft) brings higher financial benefits to the IM than RFRs (Table 6.13 and 6.14). However, the cost reduction is lower than the renewal and maintenance needs reductions and this lies in the fact that the installation of USPs is about 40% more expensive than RFRs. Considering the installation of mono-block sleepers with USPs, it is found that the use of soft USPs generate marginally higher (3 – 4%) lifecycle cost benefits (as measured by their NPV) compared to those from the installation of stiff USPs. However, the installation of soft as opposed to stiff USPs, results to lower carbon cost savings (Table 6.13 and 6.14), due to their higher carbon impact per metre of installation (2.1 times that of stiff USPs), which offsets the benefits from the reduced maintenance and renewal cycles.

TABLE 6.11: Summary of discounted costs per work description for the ECML. Units: £k.

Work Description		Base case	Ballast variant	USP (stiff)	USP (soft)	TB + USP (stiff)	TB + USP (soft)	RFRs	RPS
Renewal	Complete Renewal & Traxcavation	95,381	89,499	91,159	90,499	91,564	91,409	92,092	88,421
	ReSleeper Ballast Traxcavation	5,508	4,009	4,068	4,004	4,164	4,056	4,076	3,844
	Rerail	9,031	9,604	9,658	9,736	9,632	9,638	9,472	9,745
	S&C Renewal	35,023	18,899	18,617	18,388	18,889	18,808	19,442	18,192
	Complete Renewal with Steel	345	345	345	345	345	345	345	345
Renewal & Maintenance	Single rail renewal	3,684	3,689	3,689	3,689	3,689	3,689	3,690	3,690
Maintenance	Rail Repair (Lateral + Vertical)	11,647	11,777	11,792	11,802	11,780	11,781	11,759	11,806
	Tamping	10,068	9,777	9,749	9,711	9,774	9,755	9,787	9,677
	Stoneblowing	5,021	4,321	4,254	4,224	4,274	4,273	4,372	4,187
	S&C Tamping	4,897	4,390	4,289	4,265	4,344	4,312	4,425	4,218
	Rail Grinding	14,900	15,000	15,008	15,006	15,004	15,008	15,003	15,015
Inspection	Visual inspection	9,028	9,028	9,028	9,028	9,028	9,028	9,028	9,028
	Geometry recording	6,329	6,329	6,329	6,329	6,329	6,329	6,329	6,329
	Ultrasonic test unit	4,981	4,981	4,981	4,981	4,981	4,981	4,981	4,981
	Pedestrian Ultrasonic	4,198	4,198	4,198	4,198	4,198	4,198	4,198	4,198
LCC		220,041	195,847	197,165	196,207	197,995	197,609	199,001	193,677
NPV in 2009 prices		n/a	24,193	22,876	23,834	22,046	22,432	21,040	26,364
		n/a	12.4%	11.6%	12.1%	11.1%	11.4%	10.6%	13.6%
NPV in 2021 prices		n/a	30,265	28,617	29,814	27,578	28,061	26,320	32,980

TABLE 6.12: Summary of discounted costs per work description for the Portsmouth (Direct) Line. Units: £k.

Work Description		Base case	Ballast variant	USP (stiff)	USP (soft)	TB + USP (stiff)	TB + USP (soft)	RFRs	RPS
Renewal	Complete Renewal & Traxcavation	75,597	64,818	65,826	65,241	66,469	66,085	66,958	63,488
	ReSleeper Ballast Traxcavation	4,851	911	929	940	930	930	979	898
	Rerail	6.598	7,111	7,142	7,179	7,102	7,116	7,049	7,215
	S&C Renewal	27,501	20,920	20,852	20,815	20,748	20,920	21,318	20,414
	Complete Renewal with Steel	0	0	0	0	0	0	0	0
Renewal & Maintenance	Single rail renewal	10,784	11,691	11,673	11,733	11,660	11,704	11,630	11,733
Maintenance	Rail Repair (Lateral + Vertical)	34,043	34,279	34,273	34,297	34,263	34,279	34,241	34,300
	Tamping	3,779	3,816	3,809	3,812	3,818	3,807	3,817	3,814
	Stoneblowing	3,324	2,495	2,421	2,341	2,436	2,455	2,557	2,284
	S&C Tamping	4,321	3,950	3,905	3,849	3,993	3,923	3,973	3,837
	Rail Grinding	19,348	19,702	19,704	19,681	19,699	19,695	19,637	19,692
Inspection	Visual inspection	5,428	5,428	5,428	5,428	5,428	5,428	5,428	5,428
	Geometry recording	2,944	2,944	2,944	2,944	2,944	2,944	2,944	2,944
	Ultrasonic test unit	2,326	2,326	2,326	2,326	2,326	2,326	2,326	2,326
	Pedestrian Ultrasonic	1,999	1,999	1,999	1,999	1,999	1,999	1,999	1,999
LCC		202,843	182,389	183,231	182,584	183,815	183,609	184,876	180,370
NPV in 2009 prices		n/a	20,453	19,612	20,259	19,028	19,234	17,966	22,473
		n/a	11.2%	10.7%	11.1%	10.4%	10.5%	9.7%	12.5%
NPV in 2021 prices		n/a	25,586	24,533	25,342	23,803	24,060	22,475	28,112

Third, soft modifications (e.g. RPS, ballast variant) have the highest potential for reducing LCC owing to their lower capital costs relative to the improvement they offer in track quality. In detail, the installation of RPS track leads to higher cost benefits by 9.0 to 25.3% for the ECML and 9.9 to 25.1% for the Portsmouth line, when compared with the remaining track interventions (Table 6.13 and 6.14).

Fourth, looking at the results for all interventions (irrespective of route), the IRR is much greater than the test discount rate used, this means that choosing any of these options will result in a positive net present value. As highlighted earlier, soft modifications (ballast variant and RPS) exhibit the highest IRR, which ranges between 92.0 to 199.6% for the installation of ballast with finer gradation, and 59.9 to 110.8% for the installation of RPS track. For the remaining interventions, the IRR is broadly similar, ranging between 31.4 to 38.3% for the ECML and 41.3 to 54.2% for the Portsmouth (Direct) Line. Finally, greater rates of return are observed for the London – Portsmouth route, although in terms of NPV, an investment on the ECML will yield higher savings in absolute terms. However, when these figures are calculated per track mile the results would again favour the London – Portsmouth route.

TABLE 6.13: Decision criteria for the ECML.

Statistics	USP (stiff)	USP (soft)	RFRs	TB + USP (stiff)	TB + USP (soft)	Ballast variant	RPS	Unit
NPV[1,2]	28,617 (235)	29,814 (244)	26,320 (216)	27,578 (226)	28,061 (230)	30,265 (248)	32,980 (270)	£k
IRR	31.963	32.347	38.286	31.417	31.678	92.067	59.935	%
DPB	7	7	5	7	7	2	4	years
CC[1,3]	2,374 (19)	2,161 (18)	1,772 (15)	3,262 (27)	3,068 (25)	2,459 (20)	2,819 (23)	£k

[1] 2021 prices.
[2] NPV per mile of track inside the parentheses.
[3] CC savings per mile of track inside the parentheses.

TABLE 6.14: Decision criteria for the Portsmouth (Direct) Line.

Statistics	USP (stiff)	USP (soft)	RFRs	TB + USP (stiff)	TB + USP (soft)	Ballast variant	RPS	Unit
NPV[1,2]	24,533 (332)	25,342 (342)	22,475 (304)	23,803 (322)	24,060 (325)	25,586 (346)	28,112 (380)	£k
IRR	41.990	43.827	54.214	41.353	41.255	199.581	110.824	%
DPB	3	3	2	4	3	1	2	years
CC[1,3]	2,869 (39)	2,745 (37)	2,360 (32)	3,449 (47)	3,305 (45)	2,915 (39)	3,244 (44)	£k

[1] 2021 prices.
[2] NPV per mile of track inside the parentheses.
[3] CC savings per mile of track inside the parentheses.

Finally, for the London – Portsmouth route the two main differences lie in the complete renewal and traxcavation, re-sleeper ballast traxcavation, and in stoneblowing. For the ECML the majority of the savings are in S&C renewals. The main benefits therefore lie in the reduction of the use of materials which are comprised mainly of steel and concrete[1] on the one hand, and less use of maintenance machines on the other. To achieve greater financial benefits,

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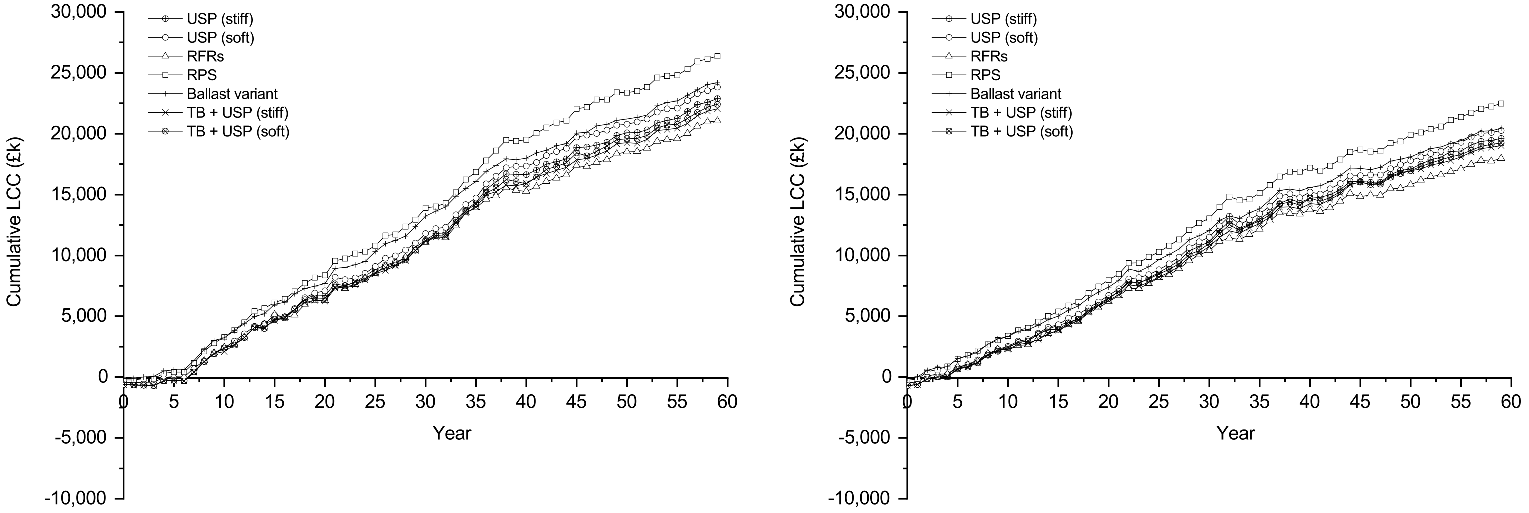
[1] These benefits relate to the reductions in complete renewals with traxcavation, sleeper and ballast renewals, and S&C renewals.

interventions that reduce the use of new material should be incentivised over interventions that reduce maintenance needs.

To have a clear picture of the differences in the LCC between these interventions and the base case, Figure 6.14 represents the accumulated difference each year in LCC. Figure 6.14 shows that the cash flows of each intervention, compared with the base case is worse for the first few years, but as the costs/benefits are discounted and accumulated the situation quickly reverses.

For the London – Portsmouth route the break-even point is achieved in year 3 with USPs (stiff or soft) and 2 with RFRs or RPS. Similarly, it will take around 3 to 4 years from the first installation of twin-block sleepers with soft or stiff USPs to break-even. Notably the choice of alternative ballast gradation, which is also the cheapest form of modification will break-even just about 1 year after the first installation. For the Newcastle – Edinburgh route the maintenance and renewals impact would be positive after 5 years with RFRs or 7 years with USPs (stiff or soft). Similarly, it will take around 7 years from the first installation of twin-block sleepers with soft or stiff USPs to break-even. Once again soft modification will break-even faster than any of the other alternatives (e.g. after 2 and 4 years for the ballast variant and RPS, respectively). Consequently, under all scenarios the payback period is relatively short. These figures are also reported for each route in Table 6.13 and 6.14.



(A) ECML.

(B) Portsmouth (Direct) Line.

FIGURE 6.14: Cumulative LCC over time.

6.3.5 Monte Carlo Simulation

In order to overcome the inherent risks to the analysis, it has been decided to implement an MCS (Kalos and Whitlock, 2008) module in Python. The model created is capable of simulating any number of variables (selected by the user), for a number of different distributions (defined by the user). The module is programmed to accommodate some of the most commonly utilised distributions for asset management problems, such as, normal, triangular, uniform, gamma, Erlang, etc.

In the whole-life model, the following targeted functions have been selected:

1. NPV
2. IRR (%)
3. DPB (years)
4. Carbon Costs (£k)

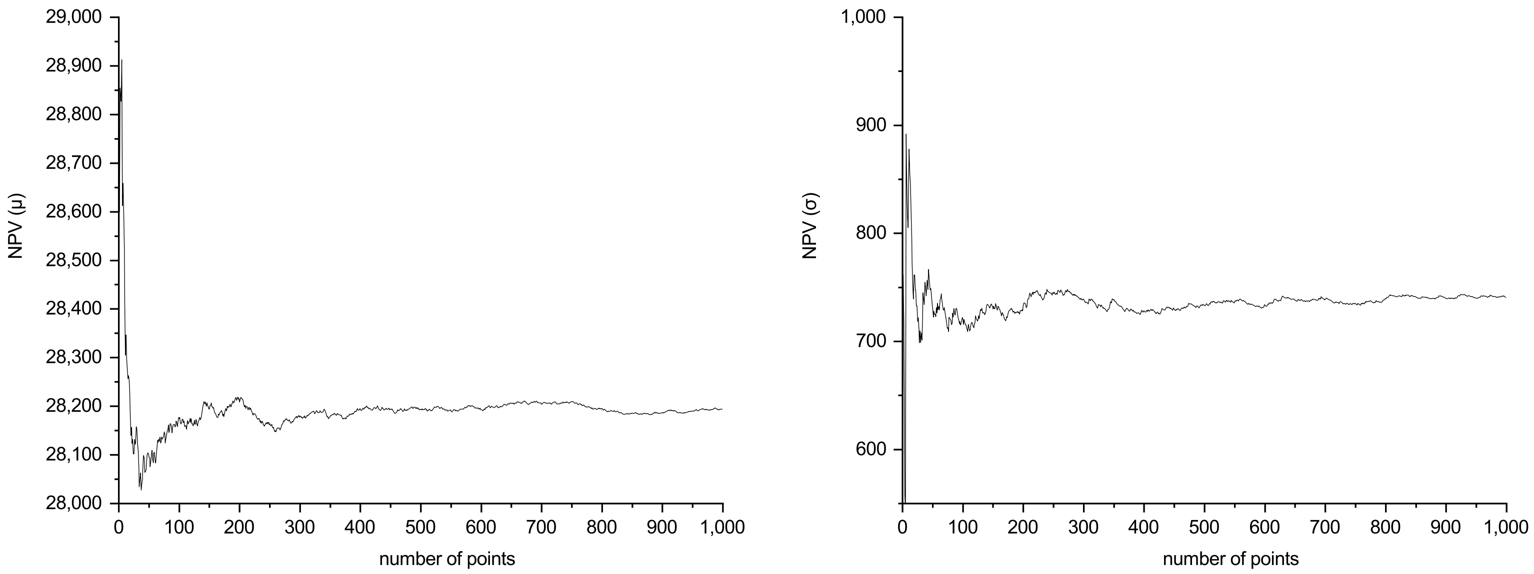
For illustrative purposes, as historical data for our parameters of interest were not available, it has been decided to create a number of pseudo-distributions for each variable in order to run simulations for each intervention scenario. Considering this, four different variables of uncertainty have been selected. Once again, the goal of the adopted method was to assess the risk associated with these estimates, choosing randomly modifiable values in each iteration. In terms of simulation details, MCS samples were of size 10,000 for each of the intervention scenarios. It was assumed that the transport distance for materials, labour and plant is a uniformly distributed random variable. Similarly, it was considered that the evaluated annual cost of carbon is triangularly-distributed; with the minimum, maximum, and mode being calculated based on the target-consistent marginal abatement costs given as a three-point estimate by DfT (2019). The unit costs for each intervention have been assumed to follow a Gaussian distribution (Sasidharan et al., 2020), which was assumed to be truncated, to avoid negative values for any of the unit costs. Finally, the carbon impacts of renewal of fifteen S&C designs (normalised per metre of double track) as calculated in Chapter 5 have been plotted in a histogram to infer their distribution. Given the resulting shape, it was assumed that this variable follows a Gaussian distribution (truncated), with a μ, σ, upper and lower bounds, being selected based on the outputs (Table 6.6) from the model presented in Chapter 5.

In order to ensure that the models converge, the mean (μ) and standard deviation (σ) for each function have been plotted against the number of simulation points. As an example, the variation of NPV (μ) and (σ) for the installation of mono-block sleepers with stiff USP on the ECML is plotted in Figure 6.15. As it can be inferred, after around 1,000 function simulations, both function values achieve convergence.

A summary of the MCS results for each function for the ECML and Portsmouth (Direct) line, is shown in Table 6.15 and 6.16 below. Looking at these results, it can be inferred that the economic and environmental performance of each intervention remains fairly stable overall, recording similar values to the results of the deterministic model presented in Table 6.13 and 6.14. The results confirm that soft modifications offer greater NPV than the remaining interventions and with greater certainty, as measured by their lower σ. Similar observations are made for the DPB, which displays low variability and appears to be shorter for softer modifications. The only competitive alternative in terms of DPB is the inclusion of RFRs. However, this option offers the lowest benefits in terms of NPV and carbon cost savings.

Regarding the carbon cost savings, these appear to be fairly stable between intervention scenarios, with low variability, as measured by their σ. This suggests that the underlying uncertainty in the values of carbon and the impact of S&C renewals does not significantly alter the results at the route level. From these results, the installation of twin-block sleepers with USPs appears to offer the best performance in terms of carbon cost savings, followed by soft track modification, such as the use of ballast with finer gradation or RPS track.

Considering the IRR, higher variability of this statistic is observed for the RPS track and the installation of ballast with finer gradation. Nevertheless, both of these interventions offer the highest rates of return over the whole simulated period, with higher values being estimated for the London – Portsmouth route.



(A) Mean (μ) of the NPV.

(B) Standard deviation (σ) of the NPV.

FIGURE 6.15: Evolution of NPV mean and standard deviation with the number of simulations.

TABLE 6.15: MCS results. Decision criteria for the ECML.

Statistics	USP (stiff)	USP (soft)	RFRs	TB + USP (stiff)	TB + USP (soft)	Ballast variant	RPS	Unit
NPV[1,2]	28,193.77 (736.78)	29,402.83 (739.51)	26,029.44 (529.41)	27,167.00 (752.96)	27,639.61 (742.53)	30,187.41 (139.76)	32,825.80 (283.27)	£k
IRR[1]	30.26 (3.48)	30.69 (3.54)	36.42 (4.08)	29.82 (3.51)	30.01 (3.49)	87.79 (9.63)	57.26 (6.02)	%
DPB[1]	7.13 (0.33)	7.12 (0.32)	5.90 (1.34)	7.14 (0.35)	7.14 (0.35)	2.60 (0.73)	4.00 (0.00)	years
CC[1,2]	2,390.89 (159.07)	2,178.92 (161.42)	1,785.56 (151.34)	3,284.77 (156.41)	3,091.68 (160.30)	2,459.65 (156.04)	2,811.58 (163.01)	£k

[1] Mean (μ) and standard deviation (σ) for each statistic.

[2] 2021 prices.

TABLE 6.16: MCS results. Decision criteria for the Portsmouth (Direct) Line.

Statistics	USP (stiff)	USP (soft)	RFRs	TB + USP (stiff)	TB + USP (soft)	Ballast variant	RPS	Unit
NPV[1,2]	24,242.43 (510.64)	25,047.04 (516.66)	22,274.41 (372.49)	23,508.86 (518.45)	23,762.06 (518.04)	25,532.26 (96.70)	28,003.23 (196.76)	£k
IRR[1]	39.18 (6.21)	40.82 (6.68)	50.70 (8.47)	38.56 (6.26)	38.46 (6.16)	187.02 (28.73)	103.73 (16.28)	%
DPB[1]	4.22 (1.04)	3.85 (0.96)	2.62 (0.95)	4.21 (0.95)	4.28 (1.00)	1.61 (0.49)	2.00 (0.00)	years
CC[1,2]	2,914.44 (69.12)	2,793.00 (69.58)	2,401.15 (63.92)	3,497.32 (75.42)	3,354.61 (70.94)	2,949.53 (70.43)	3,275.00 (69.74)	£k

[1] Mean (μ) and standard deviation (σ) for each statistic.

[2] 2021 prices.

6.4 Conclusions

This chapter introduces an extended version of the modelling framework presented in chapters 4 and 5. This new model is developed based on bottom-up principles to ensure a high level of detail, which allows for whole-life cost and carbon appraisal to be carried out at different granularity levels, depending on the study scope, system boundary and data availability. This novel framework qualifies as a comparison enabling tool, which can aid both short and long-term policy decisions - technical infrastructure choices, maintenance and renewal strategies, etc. It is also highly transferable, as it can assess the whole-life environmental and financial performance of different railway assets in the UK (from individual sections to entire routes). Adding to this, the model is programmed so as to be compatible with different degradation/deterioration models, which means that its geographical scope can be extended beyond the boundaries of Great Britain.

The applicability of this framework is then tested through a study of how the whole-life carbon footprint and LCC can be measured and improved by installing a range of novel interventions at renewals on two different routes in the UK. The research modelling shows the potential for relatively modest changes in practice to result in significant GHG emission and LCC savings. Some of the key findings are summarised as follows:

A novel methodology was proposed to predict the potential for differential settlement potential along an operating length of track using settlement measurements from laboratory tests on a single sleeper bay. The relative improvement in overall settlement in the laboratory testing was implemented into the model to assess the LCC and whole-life carbon implications of a range of novel track interventions. Although the proposed methodology has proven useful for measuring the relative benefits shown in laboratory test results, more data from laboratory testing and field trials are needed to validate and/or modify the approach if the evidence shows it necessary.

It was shown that the inclusion of novel interventions at renewals brings important benefits in terms of reduced maintenance and renewal needs, and therefore less material and energy being used on the track. However, VTISM indicates that rail renewal and rail grinding may be required more frequently, although these are modelled results that need empirical verification. Moreover, track quality is also improved and therefore better ride quality can be expected.

The analysis suggests that the installation of ballast with finer gradation or the use of RPS track can bring some important benefits in terms of LCC, owing to their lower capital costs relative to the improvement they offer in track quality. It was further shown that the replacement of mono-block with twin-block sleepers (with USPs fitted on) results to the highest benefits in terms of carbon cost savings due to their sizeable reductions in GHG emissions per metre of installation, but also the improvement they offer in terms of track quality. The analysis also suggests that installing USPs at renewals provides higher LCC savings than installing RFRs. However, the payback period of USPs is on average one to two years longer than RFRs.

It was found that the IRR for all track modifications, irrespective of route, is much greater than the test discount rate, suggesting that any of these options will result in positive returns, with soft modifications (RPS and ballast variant) resulting in higher IRR values. Moreover, greater rates of return are observed for the Portsmouth (Direct) Line, although in terms of NPV, an investment on the ECML will yield higher LCC savings in absolute terms. However, when these figures are calculated per track mile the results would favour the London – Portsmouth route.

Furthermore, it was shown that the inclusion of novel interventions can bring sizeable carbon footprint savings. However, the welfare benefits (e.g. carbon cost savings) from these modifications are small in relation to the expected financial benefits for both routes. In detail, regardless of the examined intervention or route selection, these carbon cost savings represent around 6.7 to 14.5% of the financial benefits from reduced maintenance and renewal activities.

Finally, in order to overcome the inherent risks to the analysis, a MCS module has been implemented in Python. This module is capable of conducting multi-parameter simulations, for any number of variables and an extensive range of statistical distributions. A big advantage of this model is that it was programmed so as to be compatible with other models programmed in Python, in order to be able to run MCS. Therefore, if necessary, it can be used in isolation in any future applications for such simulations, and with small adjustments, it can accommodate a wider range of distributions. For illustrative purposes, the module has been tested in this case study, using a number of pseudo-distributions for each variable of interest, as historical data were not available. Considering this, in the future, the model could be improved by calibrating the MCS module for a larger number of variables, using historical data sourced from NR. This will potentially reduce the uncertainties tied to this complex model and allow for a more definitive study of different infrastructure options.

Chapter 7

Conclusions

7.1 Introduction

This chapter concludes the thesis by describing its key findings, and makes some recommendations for future research. Section 7.2 outlines the methodological contribution to knowledge made by the models presented in this thesis, and explores their advantages and disadvantages. Section 7.3 discusses on how the proposed framework could be potentially applied to different settings and provides some recommendations with respect to validation. Section 7.4 outlines the empirical findings of this research, discussing how these are placed within the academic literature and highlighting their importance. Section 7.5 summarises the outcomes of this research in relation to the initial objectives of the thesis. Section 7.6 concludes this chapter by exploring potential future pathways for this research, and makes recommendations for moving forward.

7.2 Engineering Economics : Novel Framework

This thesis presents a detailed system framework for analysing the whole-life carbon footprint and LCC of railway infrastructure. This was based on a combination of process-based LCA and LCCA methodologies, with the subsequent modelling outputs being presented under a set of standard decision criteria used in CBA. The research examines the railway track holistically, using a bottom-up approach to built the LCI, based exclusively on activity and emission data (where possible) from UK sources. This adds an important level of specificity, which was missing from past theoretical (methodological) studies and case study applications in this field, where methodology of calculating the impacts listed on LCI, as well as a detailed reporting of the inventory itself was done inadequately. This led to these models being of one-off nature, making them unusable for comparing similar technical infrastructure choices or maintenance and renewal strategies in different geographical locations or different intervention strategies in a single location. Moreover, the fact that calculation methodologies were often ill-reported or excluded in their entirety from published research, meant that reproducibility using these models is challenging. In response to this, the proposed framework was created with the intention to adhere to the following characteristics: (i) generalised and standardised, (ii) transferable, (iii) replicable, (iv) comparison-enabling. This is important as it would allow for evaluating the whole-life performance of different modifications to the railway infrastructure system.

In response to the above, the framework presented has a high degree of standardisation, which is facilitated by its detailed formulation, allowing for the subsequent introduction of data inputs in a clear and specified manner in terms of format and layout. Adding to this, as the modelling framework was built based on bottom-up principles, it gave the potential (with small modifications to the underlying formulation) for appraising the infrastructure at different granularity levels, from a single component to an entire route. This functionality was demonstrated through a series of case studies presented in Chapters 4 to 6. Moreover, aside of its granularity, the framework exhibits a high degree of spatial transferability, which allowed the examination of the whole-life cost and carbon impacts of a range of intervention strategies for different UK routes (Chapter 6).

The framework presented in this thesis was developed in two stages, with the starting models, presented in Chapters 4 and 5 being static in nature, using average ’fixed’ values for maintenance and renewal cycles of different work activities. This of course is very restrictive, particularly in cases of *ex ante* appraisals, but also *ex-post* evaluations, and in particular, for cases where the impacts of novel modifications to the railway system have to be examined. Considering this, a novel methodology was proposed to predict the potential for differential settlement development along an operating length of track using settlement measurements from laboratory tests. The relative improvement in overall settlement was then implemented into an existing industry – based asset management model to evaluate the performance improvements offered by a range of novel track interventions. The outputs of the asset management model were then linked to the modelling framework (implemented in Python) in order to assess a number of intervention scenarios. Therefore, the proposed modelling framework has three important advantages over existing models presented in the academic literature. First, it benefits from being linked to an industry – specific model, as it can appraise/evaluate existing sections/routes, diverting from purely theoretical project appraisals. Adding to this, the fact the framework is built so as to be compatible with other degradation models, means that it can be utilised by different stakeholders and practitioners, to examine a range of railway assets using their own degradation/deterioration models for variable levels of granularity, geographical and temporal boundaries, etc. Another big advantage is that it diverges from purely ’static’ appraisals based on fixed use cycles, benefiting from the use of input data from the laboratory or field trials to examine the performance of different intervention scenarios. Secondly, when compared to other similar models presented in the literature, the framework is also underpinned by a bespoke MCS module, which enables appraisals to follow a stochastic approach (which is not as common in railway LCA and LCCA studies) so as to assess the inherent risks to project appraisals of this scale and complexity. This module is capable of conducting multi-parameter simulations, for any number of variables and an extensive range of statistical distribution and is programmed as a separate ’detachable’ function, which can be utilised for different models if necessary. Finally, this framework, as opposed to earlier modelling applications, provides a more holistic cost- and carbon-benefit analysis, which allows for the trade-offs between LCC and the carbon footprint of the railway infrastructure to be investigated.

7.3 Practical implications

This study has proposed a state-of-the-art modelling framework that enables the appraisal/evaluation of existing sections/routes in the UK. As demonstrated in Chapter 6 the framework has been used successfully to assess the implications from installing a range of different railway track interventions on two different UK routes. These case studies highlighted the advantages of the proposed methodology in terms of being geographically transferable within the UK and also having the ability to assess the performance of ballasted track at different granularity levels for a range of different scenarios.

As the proposed model runs in isolation from VTISM, it has also the potential to be utilised for appraisal of railway section/routes outside the UK. However, the researcher or practitioner carrying out the appraisal/evaluation should introduce the necessary data inputs into the model for analysis. Such data inputs include material, activity, process, emission factors, unit costs, annual work volume data, etc., which are situation-specific (depend on the site, country, suppliers, IMs, etc.). These can be introduced as deterministic or stochastic inputs (or both) as the model also supports stochastic appraisal through MCS. This choice will depend on the availability of data and scope of the appraisal. The necessary input data can be easily introduced/modified by the user through Microsoft Excel input data sheets, which are utilised by the Python model for the analysis. It is worth noting that other parameters such as the analytical lifecycle and interest rates can be also modified by the user if necessary.

It is worth noting that it would be more challenging for a practitioner to evaluate the implications from installing a range of novel track interventions on different routes outside the UK (for *ex ante* appraisals) when the necessary performance data from the field are unavailable. This is due to the fact that the methodology presented in Section 6.2.5 of Chapter 6 is specifically tailored around adapting the results of laboratory (or field) tests into a suitable parameter for input into an existing track geometry degradation model used for the UK railway network by NR. This means that for assessing the impact of different modification to the system, a prospective practitioner has to use his own degradation/deterioration model to evaluate the track performance of the section/route under investigation and calculate the resulting annual volumes of work. These volumes can then serve as inputs into the proposed modelling framework for calculating the LCC and whole-life carbon footprint for different scenarios. Considering *ex post* evaluations, the appraisal process is more straightforward as the recorded annual volumes of work can be directly introduced into the framework for further calculations.

Concerning the necessary validation procedures, as the proposed modelling framework is a hybrid approach, which combines a mix of different methodologies, there is currently no single validation procedure that could be utilised. However, a mix of validation processes could be potentially implemented to the framework by prospective validators in order to ensure that the results presented in Chapters 4 – 6 are free from material misstatements and conform to the necessary criteria. For example, ISO (2019) describes the principles and requirements for validating the assumptions, limitations and methods related to GHG reporting. Therefore, it could be used to validate the analytical aspects related to the whole-life carbon footprint modelling and evaluate the validity of the quantitative emission estimates made by the framework.

7.4 Case Studies : Empirical Findings

In terms of empirical findings, this research made an original contribution by conducting three novel case studies. This was done to demonstrate the applicability of the proposed framework at variable levels of granularity: (i) component, (ii) asset, (iii) route level. The key findings from each case study are outlined in sections 7.4.1 to 7.4.3 below.

7.4.1 Component appraisal

The first case study evaluated and compared the lifecycle GHG emissions and LCC associated with the four most common sleeper types present in the UK railway network. The framework estimates successfully the embodied material, process and transport emissions linked with the lifecycle activities of construction, renewal and EoL of these designs at low and high traffic loads.

This appraisal provided a more definitive study of the carbon footprint and LCC of different railway sleepers and made comparisons against the results of previous studies, examining the reasons behind potential variations. This was the first study of its kind to provide a more holistic approach to the appraisal of railway sleepers, using bottom-up methodology, eliminating issues related to incomplete system boundaries, geographical and temporal variability of input data sets, as well as other limitations observed in previous studies. Based on the results of the analysis in Chapter 4, the following key conclusions were drawn.

Firstly, under the low traffic load scenario, the softwood sleepers appear to be the most favourable option from a GHG emissions perspective. Whereas, at high traffic loads, the concrete sleepers outperform all other variants. Secondly, the analysis revealed that the burdensome footprint of steel sleepers is being magnified at high traffic loads, mainly due to their unsuitability for heavily trafficked applications. Estimates from this scenario suggest that the steel sleeper interventions emit significantly higher (1.2 to 1.9 times) GHG emissions compared to the remaining variants. Considering the impact of EoL pathway, this was found to be a critical factor for the environmental performance of timber sleepers. This can account for anywhere between 17% to 33.7% of their total footprint, depending on the scenario selected.

Concerning the LCC of these variants, it has been found that, irrespective of the design or traffic scenario examined, their carbon costs are small, representing between 1.9 to 5.5% of the total LCC. Secondly, for heavily trafficked routes, concrete sleepers outperform all other variants, resulting in financial benefits of up to £317.8k per stkm. Conversely, for lightly trafficked routes, softwood sleepers lead to a maximum financial benefit of up to £163.4k per stkm. Finally, the installation of concrete sleepers with stiff USPs at heavily trafficked routes, may lead to additional LCC savings of around £65k to £100k per stkm, and an equivalent reduction in terms of GHG emissions of about 23 to 73 tonnes of CO_2e per stkm, which depends on the expected annual tonnage of the route. It has been also demonstrated that the use of carbon-neutral USPs can amplify these savings even further, offering a more appealing option from an environmental viewpoint.

7.4.2 Asset appraisal

The second case study was the first to the author's knowledge to investigate the cradle-to-grave GHG impacts of a wide range of railway S&C design variants used in the UK. The LCI for this appraisal was of high granularity level and it was created by following bottom-up principles, using as input data, information from AutoCAD drawings, including data in the form of BoM and BoQ, both of which were provided by Progress Rail, which serves as the primary supplier for NR. A bottom-up approach was selected in order to ensure robustness by relying exclusively on UK network-specific supply chains and production processes. Based on the results of the analysis in Chapter 5, a number of key conclusions were drawn.

Firstly, considering the impact of S&C construction, it was found that plant and machinery had the highest average contribution to these emissions, ranging between 43.04% to 45.4%. This was followed by the impact of materials and components, which accounted roughly for about 37.02% to 39.00%. By contrast, the impact of transport of labour, plant, machinery and materials had the least contribution of between 15.5% to 19.93%. The total GHG emissions from this phase was found to range between 102.4 to 458.2 tonnes of CO_2e, depending on the scenario and design examined. Secondly, it is found that parameters such as crossing angle and switch size have a significant influence on the lifecycle carbon footprint of an S&C, with higher crossing angles and switch sizes, generally resulting on average to a larger total footprint. Thirdly, when comparing equivalent designs, on average the NR60 Mark 2 variants, display marginally better performance in terms of their lifecycle carbon footprint, when compared to the NR56 vertical designs (assuming identical track performance). However, when the cumulative benefits to the super-structure and sub-structure from the introduction of the Mark 1 and Mark 2 designs are accounted for, it is found that the newly introduced designs display significant improvements in environmental performance, resulting to an average reduction in their total footprint of about 24.9%. This translates in absolute figures, at about 102.8 to 143.9 tonnes of CO_2e. Fourthly, when considering the breakdown of the whole-life carbon footprint by LCA phase, it is found that the impact of track renewals is the highest (ranging between 58.7% to 62.2%), followed by the phases of construction (23.6% to 29.1%) and maintenance (10.4% to 13.6%). Whereas, the EoL phase had the lowest average contribution, with a figure well below 2.0%, irrespective of the scenario considered.

Considering the carbon costs of these variants, it has been found that, when assuming an identical track performance across designs, the use of the NR60 Mark 2 variants, leads to carbon cost dis-benefits per metre of track installed, when compared against their equivalent NR56 vertical designs. Secondly, irrespective of scenario, the expected lifecycle carbon costs for each turnout are found to be lower than those of their equivalent crossover. Finally, when the performance benefits (see section 5.2.2) for the newly introduced NR60 Mark 2 designs are been accounted for, their use results in carbon cost benefits per metre of track installed. However, these benefits scale down for layouts with bigger switch sizes and higher crossing angles.

7.4.3 Route appraisal

The third case study was again the first, to the author's knowledge, to investigate how the whole-life carbon footprint and LCC can be measured and improved by installing a range of novel interventions on two different routes in the UK. The literature review revealed that this is a relatively under-researched area, counting only a small number of studies, with most, if not all, case study applications being theoretical, without making use of actual data from the laboratory or field trials to measure/validate the performance of the modifications to the railway track.

In response to this, a novel methodology was proposed to predict the potential for differential settlement development using settlement measurements from the laboratory. The relative improvement in overall settlement as measured from laboratory testing was implemented into the model to assess the whole-life carbon footprint and LCC of a range of novel modifications to the ballasted track. The case study results demonstrated that modest changes in practice, in the form of track interventions, may lead in significant GHG emission and LCC savings. Based on the results of the analysis in Chapter 6, a number of key conclusions were drawn.

Firstly, it was found that the installation of ballast with finer gradation or RPS track can bring some important benefits in terms of LCC, owing to their lower capital costs relative to the improvement they offer in track quality. Furthermore, it was shown that the replacement of mono-block with twin-block sleepers (with USPs fitted on) results to the highest benefits in terms of carbon cost savings due to their sizeable reductions in GHG emissions per metre of installation, but also the improvement they offer in terms of track quality. The analysis also suggests that installing USPs at renewals provides higher LCC savings than installing ballast with RFRs. However, the payback period of USPs is on average one to two years longer.

Secondly, it was found that the IRR for all track modifications, irrespective of route, is much greater that the test discount rate, suggesting that any of these options will result in positive returns, with soft modifications (RPS and ballast variant) resulting in higher IRR values. Moreover, greater rates of return are observed for the Portsmouth (Direct) Line, although in terms of NPV, an investment on the ECML will yield higher LCC savings in absolute terms. However, when these figures are calculated per track mile the results would favour the London-Portsmouth route.

Thirdly, it was shown that the inclusion of novel interventions can bring sizeable carbon footprint savings. However, the carbon cost savings from these modifications are small in relation to the expected financial benefits for both routes. In detail, regardless of the examined intervention or route selection, these carbon cost savings represent around 6.7 to 14.5% of the financial benefits from reduced maintenance and renewal activities.

7.5 Research Conclusions

In this section the research objectives set out in Section 1.5 will be compared against the outcomes of this research in order to investigate whether these have been met successfully.

Create a detailed lifecycle carbon inventory of selected novel track forms, reflecting UK practice.

A detailed lifecycle inventory has been prepared covering both plain track as well as railway S&Cs, using as much as possible data based on UK network specific supply chains and production processes.

Investigate the differences between plain track and S&C layouts in terms of their whole life carbon footprint and carbon costs.

Fifteen of the most common S&C variants have been appraised. Detailed inventories have been prepared for each design and their lifecycle carbon footprint has been quantified and compared through a range of exemplar case study scenarios. Their embodied emissions have been also normalised per metre of double track, which allows for further comparisons to be made against the embodied emissions of plain track sections.

Develop a method for using evaluations of the relative benefits of novel interventions from single element laboratory tests to assess whole route performance with respect to their impact on reducing track vertical settlement.

A methodology, based on relative settlement is proposed to adapt the results of laboratory element tests into a suitable parameter for input into an existing industry – based asset management model for evaluating whole route performance.

Study how track maintenance frequency would be affected by installing novel interventions as standard at renewals.

The proposed framework has been applied for using evaluations of the relative benefits of novel interventions from laboratory tests to assess their impact on reducing track vertical settlement and thus, decreasing track maintenance frequency requirements.

Analyse the implications of novel interventions for LCC and whole life carbon footprint, in order to establish the extent to which these are an improvement over the existing system.

The finalised framework has been utilised to examine the implications (in terms of LCC and carbon footprint) from installing seven novel track interventions on two different routes in the UK.

Develop and use an improved, more generalised and standardised, transferable, replicable and comparison-enabling approach to the socio-economic assessment of such interventions.

The finalised methodological framework was created with the intention to adhere to the following characteristics: (i) generalised and standardised, (ii) transferable, (iii) replicable, (iv) comparison-enabling. The framework presented in this research has a high degree of standardisation, which is facilitated by its detailed formulation, allowing for the subsequent introduction of data inputs in a clear and specified manner in terms of format and layout.

Adding to this, as the framework was built based on bottom-up principles, it gave the potential (with small modifications to the underlying formulation) for appraising the infrastructure at different granularity levels, from a single component to an entire route. This functionality was demonstrated through a series of case studies presented in Chapters 4 to 6. Moreover, aside of its granularity, the framework exhibits a high degree of spatial transferability, which allowed the examination of the whole-life cost and carbon footprint of a range of intervention strategies for different UK routes (Chapter 6).

Therefore, the aims set out at for this research have been successfully fulfilled, and a detailed methodological framework now exists which allows us to investigate the potential of a range of novel interventions to reduce the whole life carbon footprint and LCC of ballasted track.

7.6 Sustainable Railways : track to the future

Considering future developments in this area, there is a number of potential pathways for improving the models presented in this thesis. First, it would be invaluable to improve the underlying LCI of these models, to account for a more extensive list of environmental impact indicators, so as to provide a more definitive appraisal of the railway infrastructure. This will facilitate more holistic analyses, and transform the modelling framework to a whole-life environmental and economic tool, which is crucial as environmental comparisons cannot be solely made on the grounds of GHG emissions. This of course is very challenging, as it will require a large amount of primary and secondary data from different stakeholders, which is not surprising given the complexity and the multi-faceted nature of the railway system. This challenge can be addressed in the future, through the development of a number of standardised forms for primary activity, process and emissions data collection, a recent example of such development has been proposed by Navaei et al. (2022).

Data can be also provided through other means, such as the use of remote condition monitoring, as well as the development and use of digital twins (Kaewunruen and Xu, 2018; Kaewunruen and Lian, 2019; Kaewunruen et al., 2020, 2021), which will help on delivering insights on the performance of different railway assets, and enable more efficient asset management. All this information can be also potentially structured into an ontology (Tutcher et al., 2017; Armstrong et al., 2020). The use of an ontology-based approach would smooth the entire modelling process by better integrating relevant data (from poorly- or non-integrated data systems) on the appropriate format and shortening/eliminating the data purification and consolidation processes (Armstrong et al., 2020).

Second, it would be of interest to account for year-on-year temporal variations of the primary/secondary data within the analytical horizons considered by the model, to account for example, for technological developments, changes in the energy mix, etc. within the temporal cycle used in the analysis, which can/will be likely to impact the final results. Potentially, it would be possible to account for these uncertainties, by using historical data to form input distributions for different variables and run simulations using the proposed MCS module. Similar, approach can be followed for updating the maintenance and renewal cycles adopted, particularly for the second case study, where historical data on the performance of different S&C designs were not available. It is worth noting here, that the use of Bayesian statistical methods can be also proven useful as they will allow for prior expectations to be updated in the light of new evidence/data becoming available.

Third, from a whole-life cost perspective, future case studies, should also account for other elements of the wider social cost, such as for example, the impacts of air-borne and ground-borne noise (refer to Young et al. (2020)), as these will have an impact and may further alter the rankings of different interventions.

Although this thesis explored a wide range of modifications to the traditional ballasted track, there is a scope of examining other interventions, as well as combinations between these. Considering this, the final model (presented in Chapter 6) can facilitate the analysis of different intervention scenarios, providing that further laboratory testing and field trials are carried out to support their viability for improving track performance. It is important to highlight here, that although the proposed approach has proven useful for measuring the relative benefits of track modifications shown in the laboratory, more data from field trials are necessary to validate and/or modify the proposed methodology if the evidence deem it necessary.

Moreover, as the proposed modelling framework calculates the year-on-year estimates at the route level, it will be beneficial to segment the route under investigation into shorter track sections for analyses, and link each of these to a bespoke software supporting the visualisation of geographic data, such as GIS using their track identifier. This will allow practitioners to better visualise and identify the carbon/environmental and economic hotspots of a given route over time and accordingly, formulate strategies to better manage the infrastructure.

Ideally future developments should also traverse from linear cradle-to-grave to a ’more’ circular methodology, effectively closing the loop, leading to a cradle-to-cradle approach (Corona et al., 2019; Moraga et al., 2019; Saidani et al., 2019). This will provide important benefits from an IM’s point of view in terms of minimising resource use and material waste, leading to both environmental and financial savings, embodying in this way Circular Economy (CE) principles (Pearce and Turner, 1990) in asset management. The first step towards this, should include the collection of process specific data for the EoL pathways of different infrastructure components, which will allow to test a number of strategies and identify the best available options, ensuring a positive environmental balance.

Concluding, there is also a scope for substituting VTISM with an alternative track degradation modelling approach. This can be beneficial as it would provide further temporal/geographical flexibility on the underlying framework, as well as allow it to divert from its formulation, which remains something of a ‘black box’. Of the available approaches, empirical (data-driven) techniques (PN, ANN, Markov Chain models, etc.) appear to be more suitable for integration within the existing asset management framework, when compared to physics-based models (mechanistic).

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