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Risk-informed sustainable asset management of railway tracks

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Risk-informed sustainable asset management of railway track

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Abstract (150 – 200 words)

Railway track infrastructure asset management is a challenging problem with added values on safety, society and environment. With railways serving as a key sustainable mode of transportation for passengers and freight, the industry is facing an increasing demand to expand its capacity, availability and speed, resulting in faster deterioration of the aging railway track infrastructure. Given the constrained maintenance budgets and the environmental challenges posed by climate change, railway asset managers have to identify economically and environmentally-justifiable track maintenance strategies without compromising on safety. To this end, this paper proposes a risk-informed approach to arrive at sustainable railway track maintenance strategies, while considering the associated track maintenance costs and impacts to train operation (environmental emissions and risk of derailments). Monte Carlo simulation is employed to address data uncertainties associated with track quality data, the costs and benefits of track maintenance and train operation. The proposed approach is successfully applied to the heavy haul railway lines in Sweden and Australia to compare some alternative maintenance strategies and identify the sustainable one.

Keywords chosen from ICE Publishing list

Railway tracks; Infrastructure planning; Safety & hazards; Maintenance & inspection; Sustainability

List of notations (examples below)

^ signifies the uncertain value

$\hat{C}_{MQ}$ is the direct costs of maintaining the railway track at an average track quality, *Q*

$\hat{C}_{In}$ is the cumulative cost of inspections during a given year, *n*

$\hat{C}_{Tn}$ is the cumulative cost of tamping during a given year, *n*

$\hat{C}_{RMn}$ is the cumulative cost of routine maintenance during a given year, *n*

$\hat{C}_{BCn}$ is the cumulative cost of ballast cleaning during a given year, *n*

$\hat{C}_{ENVQ_n}$ is the environmental cost incurred due to pollutant type, *p*, during train operation estimated as a function of track quality, *Q*, in a given year, *n*

$\hat{C}_{pn}$ is the impact cost of pollutant type, *p*, during a given year, *n*

$\hat{E}_{pn}$ is the amount of emission of pollutant type, *p*, during train operation estimated as a function of track quality, *Q*, in a given year, *n*

$\hat{P}_{DQn}$ is derailment rate associated with an average track quality, *Q*, in a given year, *n*

N is the analysis period in years

Q	is the average track quality
r	is the discount rate
$\hat{R}_{DQn}$	is the risk of derailment associated with an average track quality, Q, in a given year, n
$\hat{S}_{DQn}$	is the severity of derailment associated with an average track quality, Q, in a given year, n
T_{VP}	is the vertical track geometry expressed in standard deviations (mm)

1. Introduction

Railways not only serve as a key mode of transportation of passenger and freight traffic in urban, suburban, regional and national levels but also drive economic development, influence land use, urban planning, impact the environment and enhance liveability. They are often seen as a greener, more efficient and safer option than road transport, and thus serves as a major component within the sustainable public transport policy of many countries (RSSB, 2016; Evans, 2013). Many countries have set ambitious environmental targets for their railway industry. For example, the UK railway industry aims to cut its carbon emissions by 80% and Germany is targeting a completely CO_2 free railway transport, both by 2050 (UNCRD, 2017). Indeed, achieving sustainability has become a fundamental goal of transport planning and policy worldwide (Castillo et al., 2010). Sustainability, a concept introduced by the UN Brundtland Commission (1987), can be defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. Within transportation, sustainability can be considered in terms of equity, economy and ecology (Burrow et al., 2016). A balance between these three objectives can be achieved only when there is a trade-off between economic development and its impacts on the environment and human life (May et al., 2007).

Since 1975, global rail passenger activity has grown by 130% and freight by 76% (UIC, 2017). Such an increasing trend of usage has resulted in accelerated degradation of railway assets, higher associated maintenance costs, rise in safety risks and environmental emissions (Sasidharan et al, 2020a, Hayes et al., 2019; Mattioli, 2016;). Given the pressure to increase track utilisation, the ageing infrastructure on which much of the world's railway transport systems are founded, and the constrained budgets under which the infrastructure is managed, sustainable maintenance strategies need to be predicted, prioritised, planned and carried out. Currently, however maintenance decisions for railway track infrastructure are largely based on time, tonnage or predetermined engineering standards, which ignores the impact on train operation (safety risks and environmental emissions), therefore do not deliver sustainability (Araujo et al., 2020; Sasidharan et al, 2020a; Atkins, 2011).

Life cycle frameworks have become an integral part of decision-making in the railway environment to support the reliability, availability, maintainability and safety of railway infrastructure assets. The existing literature on employing life cycle cost (LCC) models for informing railway asset management strategies are extensive. For example, for predicting the value of railway condition monitoring (Marquez et al., 2008); to inform maintenance strategies for railway tracks (Sasidharan et al., 2020a; Smith et al., 2017; Jones et al., 2016; Guler et al., 2013; Patra et al., 2009), switches (Vitasek et al., 2017), bridges (Frangopol et al., 2007; van Noortwijk et al., 2004), tunnels (Yuan et al., 2013), signals (Hoffart et al., 2005), overhead electric lines (Antoni et al., 2008) and rolling stock (Meynerts et al., 2017; Fourie et al., 2016). Various studies also advocate the use of risk management to inform decision making in the railway industry. For example, predicting the risk of derailments (Liu et al., 2011; He et al., 2014; Jafarian et al., 2012; Zarembski et al., 2006); failure of the track (Jamshidi et al., 2016), earthwork (Crapper, 2014; Okada and Sugiyama, 1994), drainage (Usman et al., 2017), bridge (Yang et al., 2018), tunnels (Beard, 2010), level crossings (Berrado et al., 2010), signals (Zhang et al., 2013) and rolling stock (An et al., 2007). While all these techniques demonstrate the importance of using available datasets to assess the potential risks and predict LCC, there is a paucity of knowledge associated with decision-making when there is a lack or unavailability of data (Chen Yu, 2019; Gai et al., 2019; Lesnaik et al., 2019; Yan et al., 2019; Sasidharan et al., 2017). Various risk assessment techniques such as Monte Carlo simulation (Sasidharan et al., 2020a), Bayesian (Zhang et al., 2014), Fuzzy logic (Elcheikh et al., 2016), Petri nets (Rama et al., 2016) and fault tree analysis (Ma et al., 2014) are employed to deal with such uncertainties within infrastructure asset management practices. Consequently, and in accordance with international standards on risk management such as ISO 15686-5 (ISO, 2009) and EN 60300-3-3 (BSI, 2017) there is an additional impetus to incorporate risk management within asset management processes. For example, the standardised risk management processes suggested by the railway industry in the UK (Network Rail, 2014), Sweden (Trafikverket, 2020) and Australia (Office of the National Rail Safety Regulator, 2019).

Although comprehensive performance measurement frameworks are rare in transport authorities, efforts have been made by some to incorporate sustainability concepts into the transportation planning processes (Pei et al., 2010). Figure 1 summarises conceptually how asset management and risk management sits within the wider business, political and policy-making environment, and how the aims and objectives of sustainability can be derived from these and thereafter implement the solutions/interventions. Asset management policies and strategies should be an integral part of the corporate policies and the strategies of the business as a whole. Railway infrastructure owners and managers are also required to understand and manage a variety of risks (e.g. derailments, train collisions, flooded tracks, transport of dangerous goods etc.). A clear understanding of the criticality of the infrastructure, the risk events and their potential impacts can be used to support asset management by informing the mitigation plans and the organisations' business policies. The business policies define what the organisation is aiming to achieve and why it is seeking this achievement and are usually governed by stakeholder expectations, budgets, performance indicators and other targets (Robinson, 2008). To address the issues of sustainability (i.e. economic, environmental and social), the infrastructure management needs to think beyond the technical issues and problems associated with the physical infrastructure alone. To this end, understanding the problem (e.g. GHG emissions, decarbonisation etc.) is key to informing the policymaking frameworks which could contribute to identifying sustainable solutions (e.g. electrification, predictive track maintenance regimes etc.). One of the important elements in the implementation of a sustainable strategy is to measure its progress. Several frameworks have been developed for evaluating the sustainability of strategies and policies from a transport context (Abdi et al., 2019). Such a discussion would influence the political will as the politicians once elected will be key to forming broader transport policies that influence the transport authority's decision making. Thus asset and risk management should not be separate and independent of the transport authority's business management but should be a means of interpreting corporate goals in the context of the physical infrastructure asset and its associated impacts to give a clearer focus for the activities. Figure 1 also recognises the need for data or information to contribute to the asset and risk management processes.

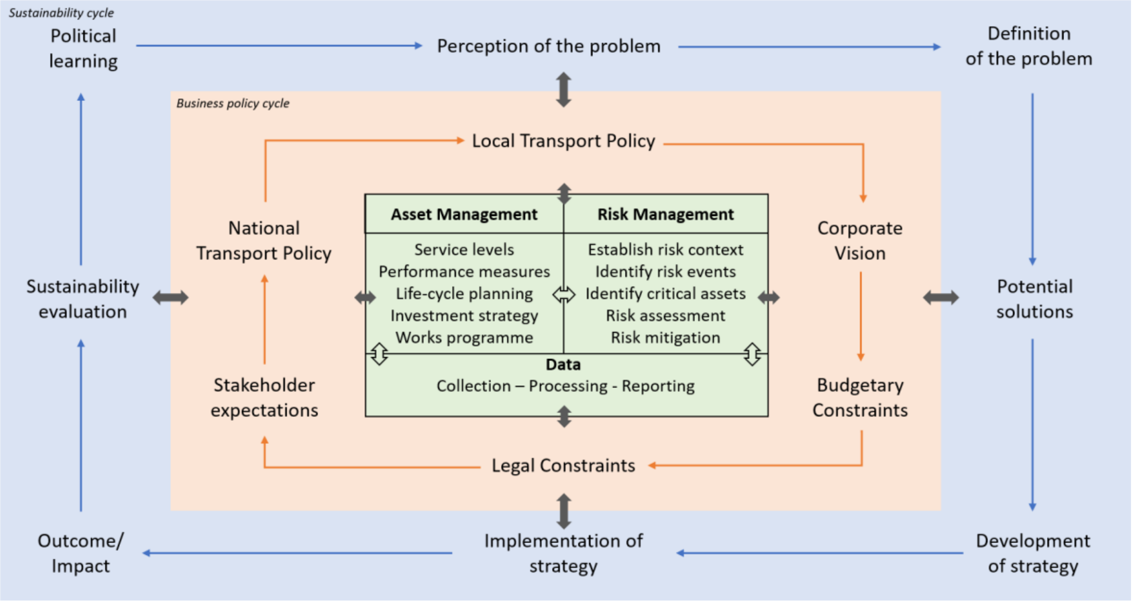


Figure 1. A framework for risk-informed sustainable asset management of railway infrastructure

Since sustainable development is becoming a dominant goal throughout the world, the public and government are pursuing green and safe objectives for the railways (RSSB, 2016). However, little of the existing literature which focuses on railway infrastructure asset management considers environmental emissions and safety risks associated with railway operation (Sasidharan et al., 2020a; Lin et al., 2017; Liu et al., 2011; He et al., 2014; Patra et al., 2009). To this end, the approach proposed within this paper (summarised in Figure 2) can be employed to compare the costs of different railway track maintenance strategies against the associated safety risks and environmental performance, to arrive at a trade-off and thus inform a sustainable maintenance strategy. The approach aids the decision-maker, who needs to define which goals need to be prioritized according to the business need/policies. The target values of each goal must be defined according to the strategy of the organisation, and the change of these values directly influences the results achieved. In addition to prioritizing the most important goals, the decision-maker could redefine the target values of their goals, seeking harmony with the possible results against existing objectives. The proposed approach is demonstrated through case studies on the heavy haul railway lines in Sweden and Australia.

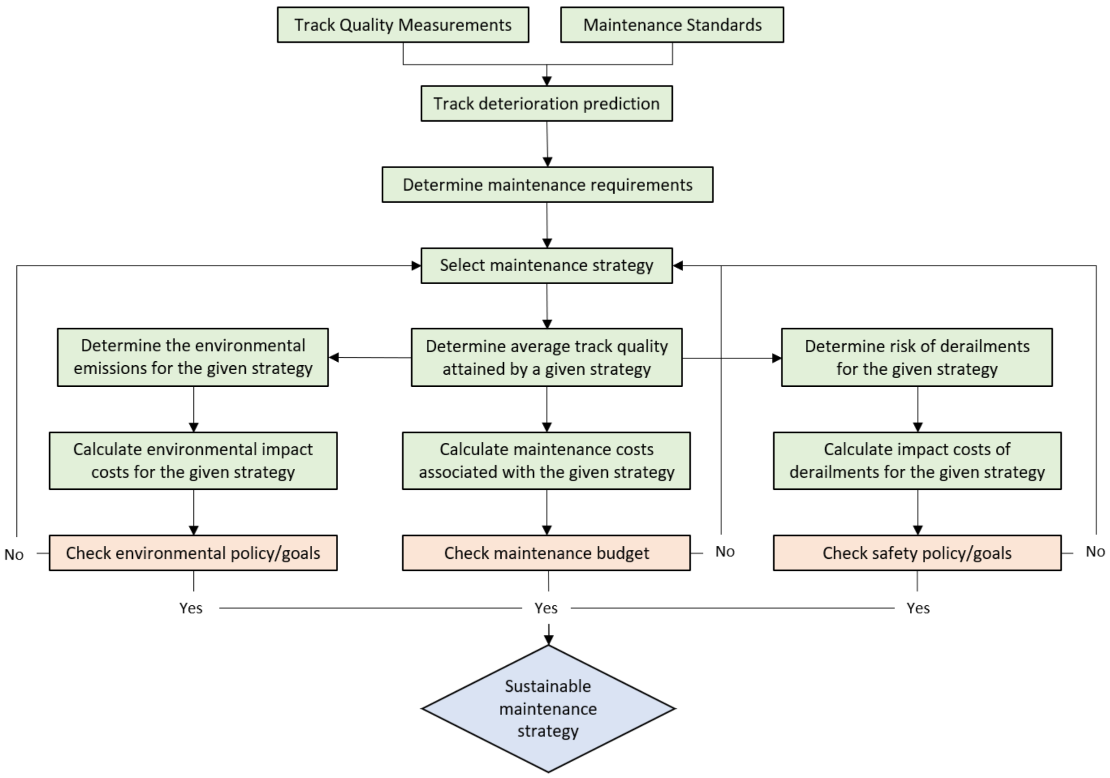


Figure 2. Risk-informed approach to setting a sustainable asset management strategy for railway tracks

2. Methodology

The risk-informed approach proposed herein for identifying sustainable railway track asset management strategy quantifies (i) the costs, environmental emissions and safety risks associated with different track maintenance strategies and (ii) takes into account uncertainty of the information to estimate, using Monte Carlo Simulation (MCS), plausible ranges of the probability of occurrence of values. The concept introduced by the UK Health and Safety Executive of measuring whether the risk presented by an alternative is “as low as reasonably practicable” (ALARP) (Nestico, 2018) is used to manage the risk of track quality-related derailments. Figure 3 illustrates the ALARP principle where the safety risks associated with different track maintenance strategies are divided into three regions. While intervention is possible if the risk falls below the broadly acceptable threshold (T_a), the risks are considered to be too high if it is above the tolerability threshold (T_t). T_a is often considered as a ‘safe level’, while T_t represents the beginning of an ‘unsafe’ area. If the risks fall within the ALARP region (between T_a and T_t), they are considered to be tolerable, provided that the costs of any further mitigation options are disproportionate to the achievable benefits. From a railway track asset management perspective, if the risks associated with a given track quality level are not tolerable, risk reduction measures must be applied or maintenance work has to be considered to lower the risk level to ALARP or broadly acceptable regions. ALARP is beneficial in cases where the primary objective is balancing the risks against the costs to reduce them and the potential benefits that can be achieved. ALARP approach was earlier applied to assess the risks associated with waterways (Bödefeld and Kloé, 2013) and for managing risks on different transport systems (Szymanek, 2008).

Since the timing of track maintenance and track use costs (including safety risks and environmental costs) vary over time as a function of track quality, it is necessary to incorporate a model of track deterioration model within the proposed approach. Such a model allows the condition of the track to be predicted at any time and thus the required maintenance and associated costs, environmental emissions and safety risks can be estimated accordingly. The usefulness of the proposed approach is demonstrated using two case studies on the Swedish and Australian railway network. The components of the developed approach are described and justified below.

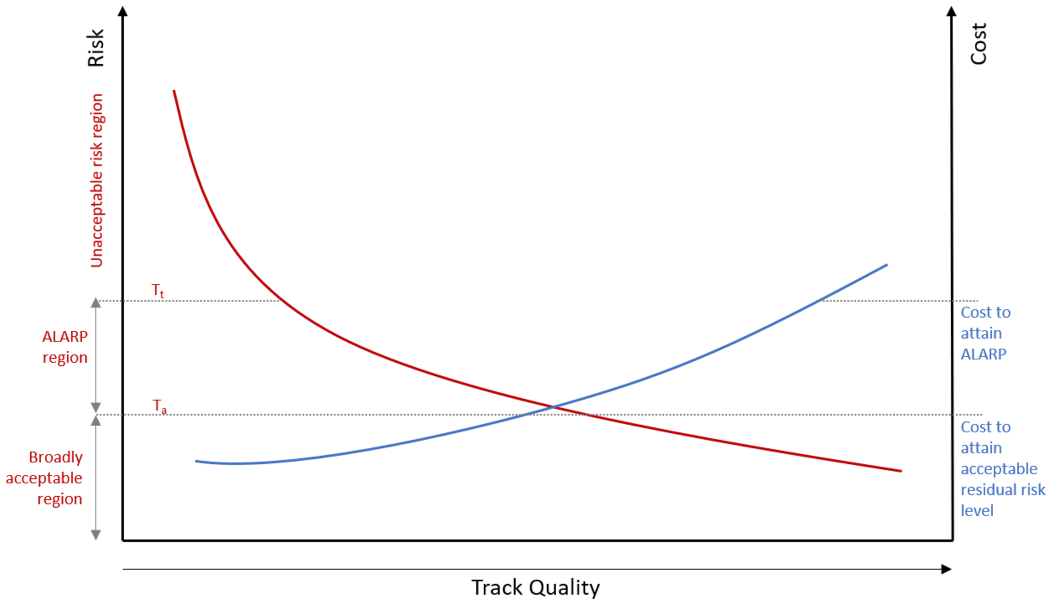


Figure 3. The principle of As Low as Reasonably Possible (ALARP) risk management

2.1 Track deterioration

Track quality is commonly quantified by standard deviations (SD) of track geometry parameters, such as vertical geometry, alignment, and cross-level; with higher Track Quality Index (TQI) depicting poorer track quality. While all the parameters are equally significant, widely used track deterioration models within the railway industry consider the prediction of vertical track settlement as the main controlling factor for track geometry and therefore for ballasted track maintenance planning (Dahlberg, 2001; Burrow et al., 2009; Sadeghi et al., 2010; Milosavijevic et al., 2012). The required track condition data can be assessed using both statistical and stochastic track deterioration models. Statistical models based on simple linear (Corbin et al., 1981) and exponential regressions (Quiroga et al., 2011) have been researched widely over the last three decades (Andrade et al., 2016). Stochastic models have also been proposed within different academic literature (Andrews et al., 2013; Zhang et al., 2014), but unlike statistical models, they have not been adopted widely within the railway industry. Monte Carlo simulation (MCS) was identified as an efficient method for such stochastic modelling (Quiroga et al., 2011), as it can be used to run hundreds of thousands of iterations before arriving at a track condition with the highest probability of occurrence for a given time. This paper adopts a stochastic track quality deterioration model using MCS suggested by Quiroga et al (2011) and assumes the track quality to be a linear function of cumulative tonnage or time and is given by Equation 1.

$$T_{VP} = (a * x) + b + e \qquad 1.$$

Where T_{VP} is the vertical track geometry expressed in standard deviations (mm), x is time or tonnage, a and b are linear coefficients and e is the error value.

2.2 Track maintenance costs

A variety of maintenance activities are carried out to treat the ballasted railway tracks. The vertical track geometry of ballasted railway track is usually restored by tamping while ballast cleaning is carried out to remove the fines within the ballasts. Routine maintenance activities such as weed spraying, vegetation removal and drainage cleaning are carried out periodically. Achieving a higher track quality requires frequent maintenance interventions, as informed by the track deterioration model (Section 2.1).

Maintenance activities involve direct costs in the form of labour, machinery and planning. These costs associated with maintaining the track to different quality levels are calculated using Equation 2.

$$\hat{C}_{MQ} = \sum_{n=0}^{N} \frac{\hat{C}_{In} + \hat{C}_{Tn} + \hat{C}_{RMn} + \hat{C}_{BCn}}{(1+\hat{r})^{n}} \qquad 2.$$

Where $\hat{C}_{MQ}$ is the direct costs of maintaining the ballasted railway track at an average track quality, *Q*, based on $\hat{C}_{In}$ as the cumulative cost of the inspection, tamping ($\hat{C}_{Tn}$), routine maintenance ($\hat{C}_{RMn}$) and ballast cleaning ($\hat{C}_{BCn}$) during a given year, *n,* with discount rate *r*.

2.3 Risk of derailments

Risk is defined as a function of system failure and the severity of losses or damages associated with the failure. While the causes of derailment are generally classified as infrastructure-, rolling stock-, and weather-related, studies have shown that the likelihood and severity of derailment increases with as track quality worsens (Sasidharan et al., 2020; Lin et al., 2019; He et al., 2015; Liu et al., 2011). The cost components of a derailment include damage to third party property and passengers' health, loss of life, damage to goods and costs involved in rescue, delays, investigation and repair and renewal of track and rolling stock. Risk of the derailment ($\hat{\hat{R}}_{DQn}$) was calculated by multiplying the average impact costs of the severity of derailment ($\hat{S}_{DQn}$) with the probability of occurrence of a derailment ($\hat{P}_{DQn}$) associated with track quality, *Q*, in a given year, *n* (Equation 3).

$$\hat{R}_{DQn} = \sum_{n=0}^{N} \frac{\hat{P}_{DQn} * \hat{S}_{DQn}}{(1+\hat{r})^{n}} \qquad 3.$$

2.4 Environmental impacts

The environmental impacts of train operation associated with CO_2 and NO_X emissions (AEA, 2008) due to deteriorating track quality had the highest contribution to the total railway transport costs (Sasidharan et al., 2020a, 2020b). The energy loss in the train suspension system increases exponentially as a function of the track quality (Zarembski et al., 2010). The track quality impacts the amount of fuel consumed by the trains which in turn releases pollutants such as CO_2 and NO_X. These pollutants cause damaging impacts on ecology and adversely affect human health. The environmental impact costs can be calculated using Equation 4.

$$\hat{C}_{ENVQ_n} = \sum_{p=1}^{P} \sum_{n=0}^{N} \frac{\hat{E}_{pQ_n} * \hat{C}_{pn}}{(1+\hat{r})^n} \qquad 4.$$

Where $\hat{C}_{ENVQ_n}$ is the environmental impact costs, $\ddot{E}_{pn}$ is the amount of emission, and $\hat{C}_{pn}$ is the impact cost incurred due to pollutant type, *p*, during train operation estimated as a function of track quality, *Q*, in a given year, *n,*

3. Case studies

The proposed risk-informed asset management approach was demonstrated for homogeneous track sections on the Iron Ore line in Sweden and Trans-Australian line in Australia. A representative section has homogeneous characteristics in terms of construction, maintenance history, traffic and the environment so that all such sections within a homogenous group may be considered to deteriorate at a similar rate (Burrow et al., 2009). For both the routes, the track quality data and maintenance history were obtained to estimate the deterioration rates. Different maintenance strategies can produce different average track qualities over time. The track deterioration model (Equation 1) was employed to identify the maintenance requirements for different levels of average track quality based on the average value of vertical SD i.e. poor (3-4 mm SD), medium (2-3 mm SD), good (1-2 mm SD) and high (0-1 mm SD) over 10 years (two-track renewal cycles). The unit costs for performing different maintenance activities (see Table 1) were applied to Equation 2 to study the total maintenance costs associated with different levels of track quality using a discount rate of 3.5%. The historical data and impact costs associated with derailments were collected and applied to Equation 3 to estimate the risk of derailments. The approach suggested by Liu et al. (2011) and Zarembski et al. (2010) were adapted to calculate the risk of derailments and fuel consumption associated with different track quality levels respectively. The quantity of CO_2 and NO_X emissions were assumed to be proportional to the fuel consumption (AEA, 2008) and the impact costs over the analysis period were calculated using Equation 4.

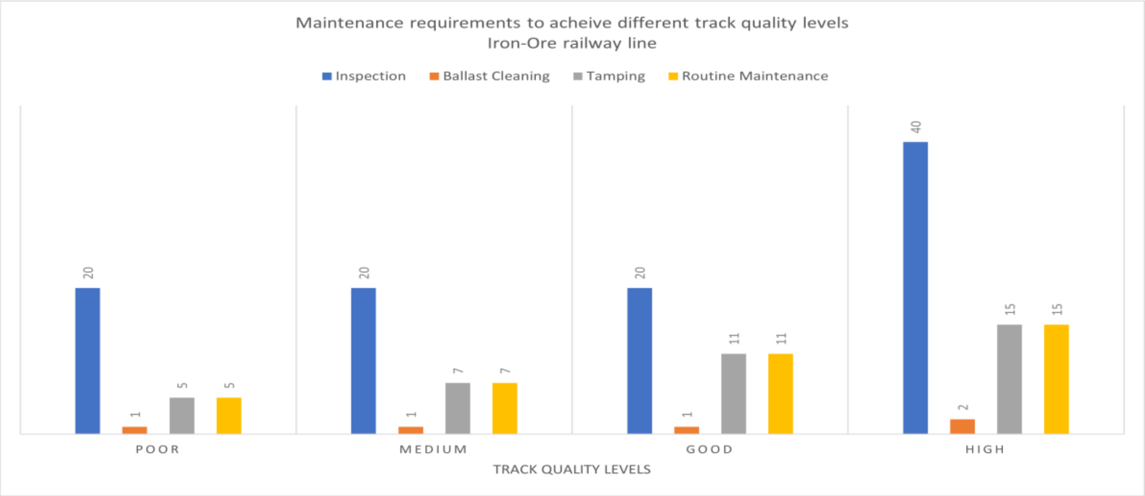
Table 1. Data used for Case Studies

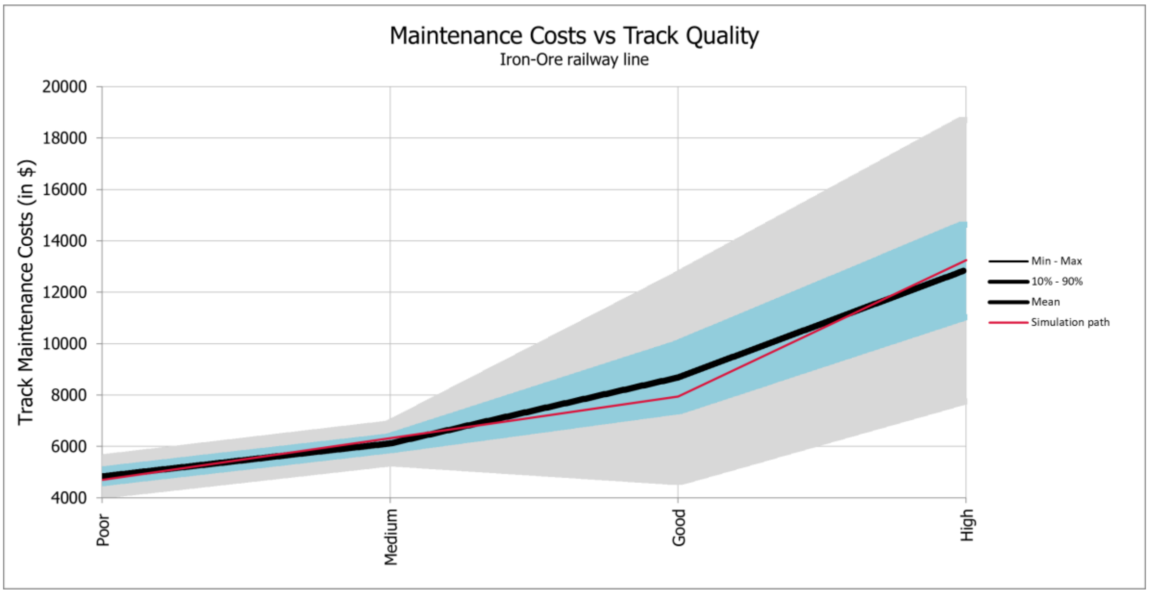
Item	Sweden	Australia	Source
Inspection cost	\$132/km	\$250/km	Personal communication with the Trafikverket, Sweden and relevant transport authority in Australia
Tamping cost	\$2208/km	\$4020/km	
Ballast Cleaning cost	\$5520/km	\$7014/km	
Routine Maintenance cost	\$1000/km	\$2000/km	
Impact cost of train derailment	\$1,656,050	\$7,230,900	
Impact cost of CO$_2$ emissions in Sweden	\$0.123/kg		Government of Sweden (2020)
Impact cost of NO$_x$ emissions in Sweden	\$0.00458/kg		OECD (2009)
Impact cost of CO$_2$ emissions in Australia	\$16.38/tonne		Australian Government (2010)
Impact cost of NO$_x$ emissions in Australia	\$0.1629/tonne		Envrion (2013)
Fuel consumed per year on Iron-Ore railway line	1711.85 kilo litres		Nordmark (2015)
Fuel consumed per year on Trans-Australian line	99,358 kilo litres		Envrion (2013)

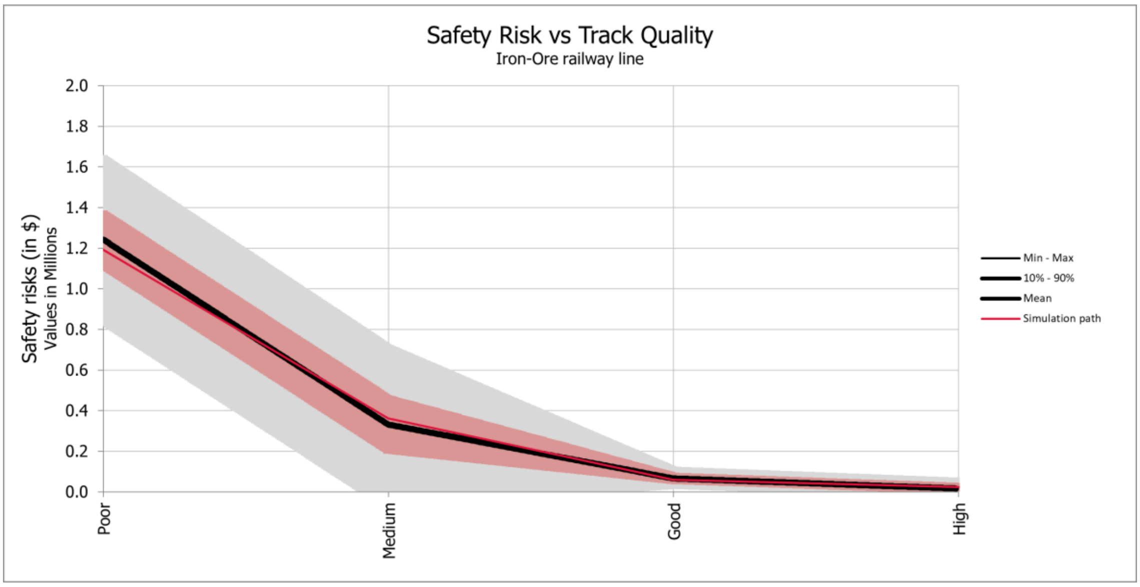
For both analysed routes, four maintenance strategies were considered in terms of the resulting track quality levels namely poor, medium, good and high; to inform their impact on environmental emissions and realising the derailment risks to an acceptable level (or ALARP). Monte Carlo simulation using @RISK© software was employed to deal with uncertainties associated with estimating the unit costs. To this end, the value with a 90% probability of occurrence (or confidence level) was obtained from 10,000 iterations.

3.1 Iron ore line

The case study was performed on a homogeneous section of the track along the 473 km long Iron Ore Line (Malmbanan), the only heavy haul line of Europe that runs between Lulea in Sweden and Narvik in Norway. Majority of the traffic on this route is dominated by iron ore freight services, connecting the mines of Gallivare and Kiruna with the ports in Narvik and Lulea, amounting to around 25-30 tonnes annually. The geographical constraints and severe weather conditions including snowstorms and sub-zero temperatures of up to -40°C, puts immense strain on the track infrastructure (Nielsen et al., 2018). The quality of the track section on the northern branch of the line (Kiruna to Narvik), deteriorates at a maximum rate of 0.9mm SD/year while following a renewal, at 0.3mm SD/year. Such higher trends in deterioration is often explained by local substructure property variations due to temperatures rising above freezing point during April to July annually (Arasteh khouy et al., 2016; Nielsen et al., 2018). The existing maintenance programme on the Swedish side of the line is based on engineering judgements and maintenance standards from Trafikverket, the track infrastructure manager for Swedish railways (Soderholm et al., 2017). The track section is currently maintained at a ‘good’ track quality level (of 1.6 mm average SD) and is inspected regularly, with the frequency of inspection being dependent on train speed, loading, geotechnical and environmental conditions. The percentage of track geometry related derailments on this route is very small i.e. approximately 0.38% of the annual accidents (Kumar et al., 2008). This study calculated the maintenance requirements (Figure 4a) and the track maintenance costs (Figure 4b) associated with different maintenance strategies. The risk cost of derailments and environmental impacts associated with different maintenance strategies are presented in Figure 4c and Figure 4d respectively.


Maintenance requirements to acheive different track quality levels
Iron-Ore railway line
Inspection
Ballast Cleaning
Tamping
Routine Maintenance
20
1
5
5
20
1
7
7
20
1
11
11
40
2
15
15
POOR
MEDIUM
GOOD
HIGH
TRACK QUALITY LEVELS


Maintenance Costs vs Track Quality
Iron-Ore railway line
Track Maintenance Costs (in $)
20000
18000
16000
14000
12000
10000
8000
6000
4000
Poor
Medium
Good
High
Min - Max
10% - 90%
Mean
Simulation path


Safety Risk vs Track Quality
Iron-Ore railway line
Safety risks (in $)
Values in Millions
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Poor
Medium
Good
High
Min - Max
10% - 90%
Mean
Simulation path

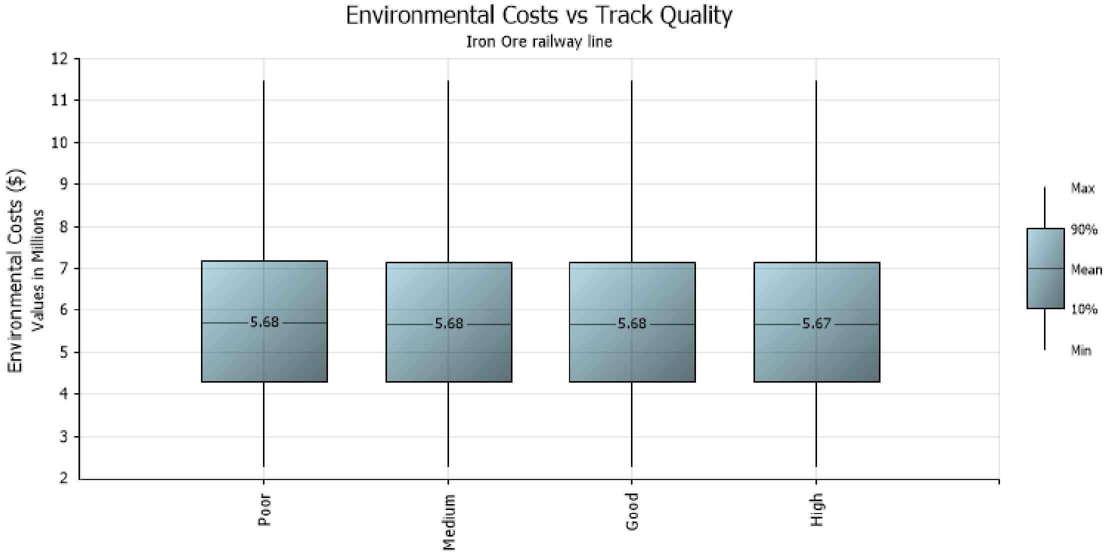
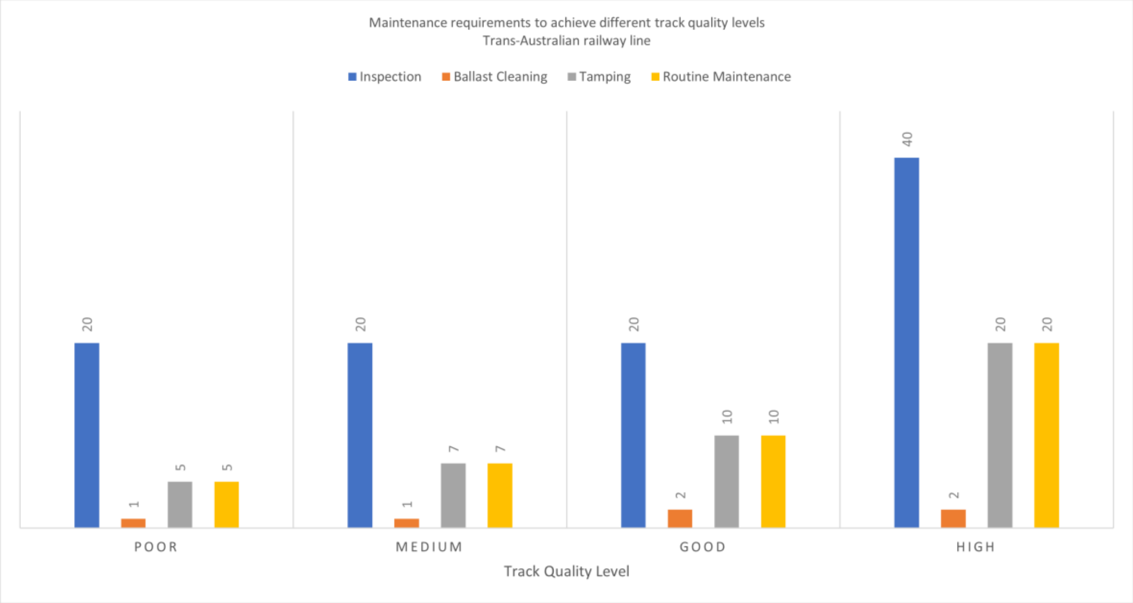
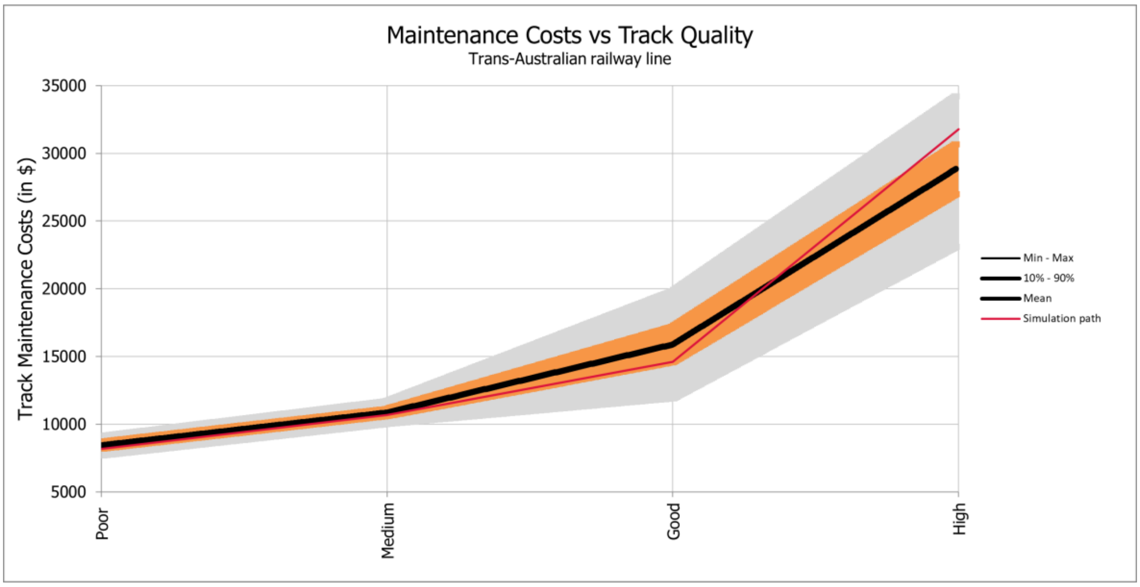


Figure 4. (a) Maintenance requirements to achieve different track quality levels; (b) Maintenance costs as a function of track quality; (c) risk of derailments; (d) environmental impacts; as a function of track quality on the Iron Ore line track section

3.2 Trans-Australian line

A homogeneous track section from the 478 km long Trans-Australian railway line that connects Port Augusta and Kalgoorlie was selected for this case study. It forms an important freight route carrying coal between western and eastern states of Australia and accommodates marginal passenger service operations. Australia's freight usage is expected to triple by 2050, and railways are currently the preferred mode of freight transport for long-distance (PWHC, 2009). Coal spillages cause ballast fouling and are the primary cause of track deterioration on these heavy haul route. Historically, track maintenance was intensified due to coal spillage related issues. The deterioration rate of the track section analysed was found to be 0.12mm SD/year, with track realignment being carried out once every 1-2 years. Currently, the track section is maintained at a poor track quality level (i.e. at 3.6 mm average SD). Ten year-long historical data-informed two derailments caused due to track quality-related faults. The maintenance requirements and associated costs estimated as a function of track quality levels are presented in Figure 5a and 5b respectively. The safety risk reduction realised from maintaining the track at medium quality instead of the current strategy provides greater benefits against the associated costs (see Figure 5a and 5c). The environmental impacts of train operation associated with different track quality levels are presented in Figure 5d.





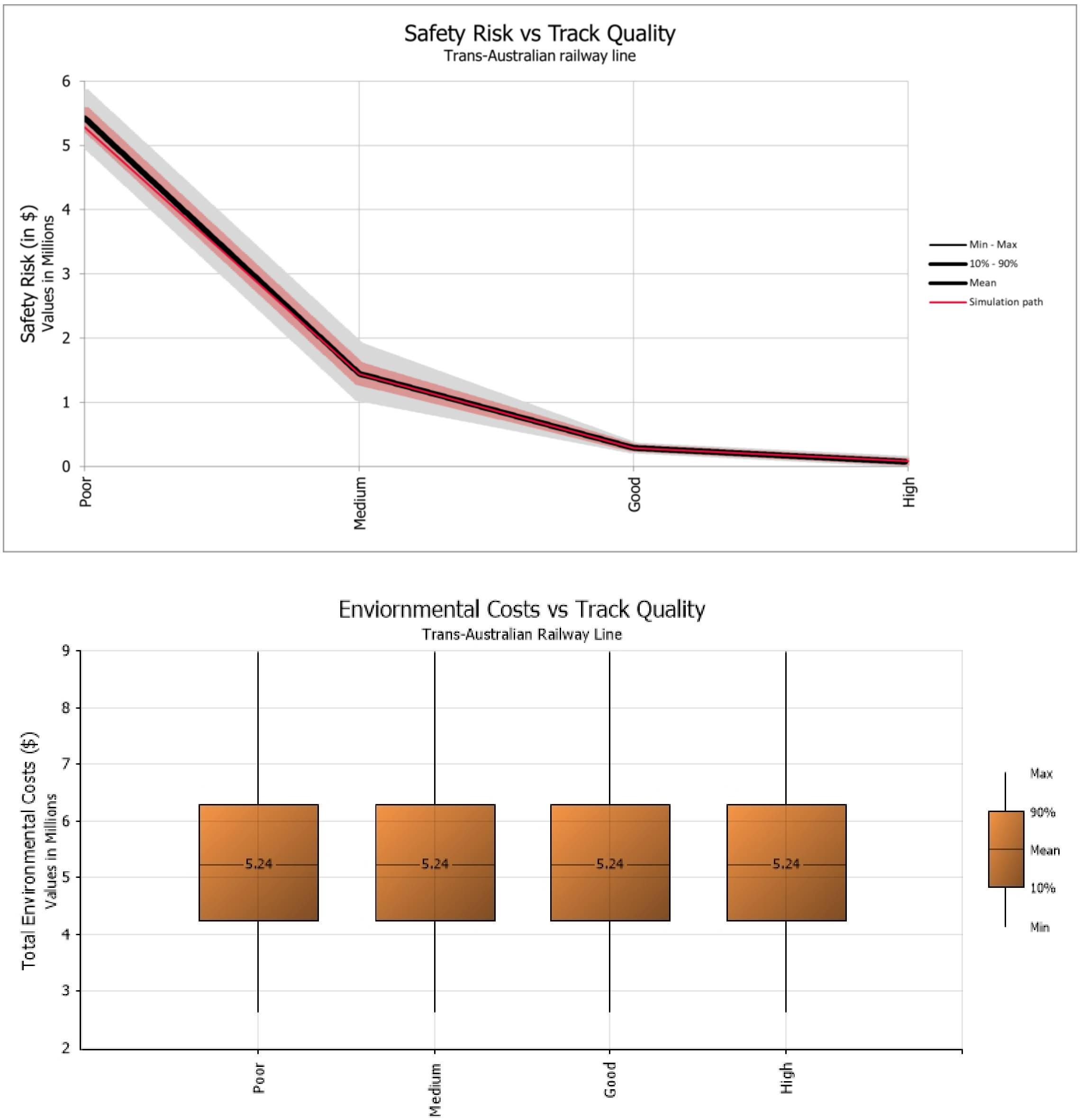


Figure 5. (a) Maintenance requirements to achieve different track quality levels; (b) Maintenance costs as a function of track quality; (c) risk of derailments; (d) environmental impacts; as a function of track quality on the Trans-Australian line track section

4. Results

The railway networks in both Sweden and Australia are managed and operated in a similar way i.e. the railway infrastructure is owned and governed by a public organisation/government, while maintenance is carried out by a separate organisation. Though both of the selected heavy-haul routes operate in different environmental conditions, the performance indicators of both the transport authorities were found to be similar i.e. safer transport and decarbonisation (Ahren et al., 2004). The risk-informed approach demonstrated within this paper could be adopted to achieve these goals. The safety performance of both lines is often compromised by the occurrence of derailments. Impact of track quality on safety risks was explored on both routes and found to have a similar trend (see Figures 4c and 5c). Four maintenance strategies were considered in terms of maintaining the track quality at poor, medium, good and high levels. With a 90% confidence, analysis on the Trans-Australian line shows that maintaining the track quality at 'medium' level would be approximately 25% costlier than the current strategy (i.e. poor) while maintaining at 'good' and 'high' qualities could cost at least 70% more. A relatively similar trend is observed on the Iron Ore line; maintaining at a 'medium' track quality is approximately 17% costlier than 'poor', with good and high costing 83% and 51% more respectively. With a 90% confidence level, maintaining the track quality at medium instead of poor level offers the maximum safety risk reduction (approximately 75%) on both the routes. Although maintaining the track at higher quality increases the direct maintenance costs, the trade-off achieved through safety improvements, reduction of delays and environmental impacts allows decision-makers in making a business case. While considering a trade-off between maintenance costs and associated safety and environmental impacts, maintaining the track sections on both the heavy haul lines in Iron Ore line and Trans-Australian line at 'medium' track quality also realises the ALARP principle. The results from the case studies show that the environmental impacts gained from maintaining the railway tracks at a higher track quality are negligible in comparison with other strategies. However, the case studies consider only the impacts from the train operation (i.e. fuel emissions) and both the routes analysed have low traffic in comparison to that of a commuter or mixed passenger-freight route. Hence, the environmental impacts gained due to maintaining railway tracks at a better track quality could be higher in such busier routes (for e.g. refer to case studies within Sasidharan et al., 2020a).

5. Concluding discussion

The continuous increase in demand on the transport networks creates a need for a risk-informed asset management strategy, particularly for railway tracks, as they are critical elements within the railway infrastructure. To improve the safety and environmental performance of the railway transport network within constrained budgets, sustainable maintenance and management strategies needs to be identified. To address this, the study has advocated a risk-informed approach to deal with uncertain information while arriving at economically and environmentally-justifiable railway track maintenance strategies while considering safety. The approach demonstrated via case studies on heavy-haul routes in Sweden and Australia showed that such sustainable track maintenance strategies can be identified effectively. Currently, track maintenance takes up 25%-35% of the freight railway line operational expenses in Australia (Indratna et al., 2012). Therefore, significant savings can be achieved if sustainable track maintenance strategies are adopted as suggested by previous studies (Laird et al, 2002).

The outputs from the proposed approach presented the risk of derailments as a function of track quality and explored the impact of different maintenance strategies on reducing the safety risks to ALARP. Reaching unanimity on the “acceptable” level of risk is nearly impossible, but consensus can be reached for many, if not most, environmental and safety management actions. The environmental benefits gained could be maximised if considered earlier within the life cycle of the railway track i.e. design and construction. For example, sourcing components which contain recycled content or using where appropriate life-expired ballast within the sub-ballast ballast layer or electrification etc. From an operational perspective, the environmental impacts from train operation as a function of track quality would be significantly higher in busier routes (Sasidharan et al., 2020a) than the ones considered within the case studies. The learnings from the presented approach will be useful for railways across the world and could inform the life-cycle decisions for new railway routes such as high-speed rail (HS2) in the UK and dedicated freight corridor in India.

The proposed risk-informed approach aids the decision-maker to compare the track infrastructure maintenance budget with the associated safety and environmental performance and thus set sustainable maintenance strategies. It can be considered to aid the three levels of decision-making namely strategic, tactical and operational. At the strategic level, senior managers or directors can evaluate and set sustainable policies and plans for the whole organisation or railway network. The framework can inform both route managers for tactical planning of works in the medium term and also asset engineers at the operational level to arrive at short-term decisions for implementing the ongoing or planned works. Considering that climate change is projected to increase the frequency and intensity of some extreme weather events, there is a need to extend current risk-based asset management systems to incorporate the effects of climate change, infrastructure interdependencies and the associated risk of railway infrastructure systems failures. To this end, railway infrastructure owners and managers should be encouraged to (i) identify the routes or sections of the network that are likely to provide maximum benefit from implementing such approaches, (ii) evaluate the physical characteristics of track infrastructure to understand the exposure to climate change or extreme events, and (iii) consider the socio-eco-environmental impacts associated with track infrastructure while budgeting for maintenance strategies.

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