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An alternative approach to railway asset management value analysis: framework development

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The management of a diverse asset portfolio is a demanding task for railway asset managers. They must ensure that the network delivers a high level of performance for customers and adheres to safety limits. Reliability, availability, maintainability and safety (RAMS) analysis is regularly used to assess the performance of systems, including railway networks. However, currently there are a wide range of different approaches to RAMS analysis in the railway industry. This research seeks to identify and consolidate any potential extensions to the traditional RAMS approach into a single framework: extended RAMS. The framework comprises ten parameters, RAMS and six additional parameters of particular interest to railway asset managers, including capacity and train performance. The framework is intended for use by asset managers to evaluate the attributes and current status of the railway infrastructure and enable comparison between different parts of the network and to evaluate different stakeholder needs.

Notation

A	occupied (used) capacity
B	unusable capacity
C	recovery allowance
D	unused capacity
$f(x)$	probability density function
$M(t)$	probability that the component is repaired within time t
$R(t)$	reliability or assessment of how often failures occur
α	line speed adjustment time
β	station adjustment time
γ	recovery allowance
δ	unused capacity
τ	maximum number of trains per hour

Introduction

Effective asset management can improve an organisation's ability to operate safely, meet regulatory obligations and significantly reduce the cost of managing assets over their lives (IAM, 2015). In the rail industry, effective asset management contributes towards delivering a more efficient railway by maximising the benefits of railway assets over their life cycle. However, to develop optimal strategies and evaluate accurate life-cycle costs, it is fundamental that the present attributes of railway operation are well understood. Only then can appropriate forecasts and objectives be set.

This study reviews existing applications of reliability, availability, maintainability and safety (RAMS) in the railway sector; it also explores extensions to the traditional RAMS approach, with the aim of consolidating these existing approaches into a single framework called extended RAMS (ExRAMS). The ExRAMS framework consists of ten parameters: RAMS and six additional parameters specifically related to railways. For each, the desired metric and definition are presented alongside current assessment metrics. The parallel paper (Litherland *et al*., 2021) then demonstrates the application of the framework through a case study and explores how the ExRAMS framework can be used to form a value framework.

RAMS analysis is a well-established discipline used to assess the life cycle of a component or system. RAMS analysis is a well-defined procedure for 'closed' systems: a system that has a finite number of components and a known permutation of series and parallel components. Moreover, to conduct a reliability, maintainability and availability (Ram) analysis, the dependencies between components and the effect of component failure on the operational system must be well understood.

In the case of a railway system, neither of the above statements holds, and therefore, the conduction of a traditional RAMS analysis breaks down. Additionally, traditional RAMS analysis does not consider many criteria such as capacity, train performance and environmental factors, among others, which are fundamental indicators of the successful operation of a railway network. The inability to apply traditional, well-defined RAMS analysis and its inability to consider several key railway criteria have led to many railway asset managers to conduct their own bespoke RAMS analysis. This has lead to inconsistency across the industry and inhibits the sharing of knowledge.

The purpose of the ExRAMS framework is to evaluate and combine the various approaches to RAMS that are currently used within the railway industry into a single framework, enabling uniform assessment of the current operation of the infrastructure in a section or route. The framework is designed for use by railway infrastructure managers (IMs) to assess the performance of the railway infrastructure. It is not designed for use by rolling stock or operation managers. The framework will facilitate the benchmarking between different routes and potentially different railway operators. The benchmarking of different routes can provide insight as to why key performance indicators may fluctuate between routes, and can even assess the effects of different operational strategies. Moreover, the holistic approach of the framework has also been used to identify a comprehensive list of required data, such that all the required data sets can be stored in a single repository.

The framework is designed to provide a means to evaluate the present attributes and current status of railway operation, over a particular section of the network or even the whole network. The framework encapsulates ten parameters that consider the present service offering and performance of the railway, as well as the performance and condition of infrastructure assets. This paper initially reviews the literature for traditional RAMS analysis, alongside the consideration of existing research into the parameterisation of the operational status of railway networks. Based on the literature review, six parameters, in addition to RAMS, are identified as critical to IMs. For each of the parameters, a definition is provided as well as a method of calculation.

Background

This section begins by introducing traditional RAMS analysis and exploring some of the bespoke extensions to RAMS analysis. These extensions will be reviewed to determine which additional parameters are of importance to railway IMs. This is followed by an evaluation of how the ExRAMS framework will interact with other assessment frameworks within the rail industry.

Traditional RAMS analysis

Ram analysis is a well-established analytical technique used to estimate the availability of a system through the assessment of potential failure modes and failure frequencies and the evaluation of inspection, servicing, maintenance and replacement characteristics of resuming system/component operation on failure. An early application of Ram analysis in the nuclear industry was shown by Cleveland *et al*. (1985), with further examples shown in the aerospace industry (Cole, 1998), chemical processing industry (Khan and Kabir, 1995) and telecommunication industry (Hamersma and Chodos, 1992).

In the nuclear industry, safety studies were performed as early as the 1950s (Beckerley, 1957), and by the 1970s, comprehensive safety reports were produced (US NRC, 1975). Towards the end of the twentieth century, following a spate of accidents such as the Chernobyl disaster (Gittus *et al*., 1988), the King’s Cross fire (Fennell, 1988), the Piper Alpha disaster (Cullen, 1990) and the Paddington rail crash (Ladbroke Grove) (Cullen, 2001), there was a renewed emphasis on improving industrial safety. In recent times, most industries are regulated by an independent safety body.

Safety and reliability analysis did not develop as a unified discipline but have merged as a result of integrating a number of activities such as reliability modelling (Smith, 2017). This caused Ram analysis to evolve into RAMS analysis. Initially, there was some debate on what the ‘S’ should represent, with some arguing it should be survivability (Hamersma and Chodos, 1992), while others argued supportability would be more appropriate (Markeset and Kumar, 2003), as opposed to the standard, safety (Breemer, 2009; Zoeteman and Braaksma, 2001). However, there is now universal agreement in the ‘S’ being safety; the industry standard for railway RAMS, BS EN 50126 (BSI, 2017), recognises the ‘S’ as safety.

The main benefits of conducting a RAMS analysis are that it can explain how the key parts of the system are functioning and highlight underperforming areas, through a quantitative assessment of components. RAMS analysis is most insightful on closed systems where the behaviour of the said components is well understood as are the interactions between them. This is demonstrated by numerous applications in industries, such as nuclear, plant and aerospace (Cleveland *et al*., 1985; Cole, 1998; Hamersma and Chodos, 1992; Khan and Kabir, 1995). Conducting a RAMS analysis can lead to reductions in maintenance and sparing costs, an increase in production levels and a decrease in the duration of any unplanned and planned outages (ESC, 2020). Nonetheless, as the system complexity expands and the relationships between components becomes less well understood, the fluidity of a traditional RAMS analysis diminishes and a quantitative assessment is no longer possible.

Due to the complexity of the railway network as a system, the relationships between components are often not fully understood, which inhibits the realisation of a traditional RAMS analysis. Moreover, even if the system was fully understood, due to the scale of railway networks, it is likely that the problem would be intractable. To resolve such concerns, many railway IMs resort to performing their own bespoke RAMS analysis.

Bespoke RAMS analysis

An international standard exists for the RAMS analysis of railway networks (BSI, 2017). However, the documented standard considers only the problem of a RAMS analysis of railways as an abstract, high-level concept. The size and complexity of railway systems has led to many asset managers introducing their own interpretations and implementations of RAMS analysis, with each implementation having a varying scope.

Many have transitioned away from the traditional mathematical definition of Ram and devised their own industry-specific metrics for their analysis, as well as including additional parameters for their specific organisational needs. This expansion of RAMS analysis has resulted in many different organisations and industries developing bespoke solutions, leading to a disjointed approach to RAMS in the railway industry and limited scope for benchmarking.

Due to the importance of performance, Network Rail often extends RAMS analysis to performance, reliability, availability, maintainability and safety (Prams) analysis (NRC, 2019). Prams projects were established to analyse and influence the impact of proposed changes on the Western Strategic Route, consistent with achieving acceptable levels of route performance (TPD, 2014).

Another example of an ExRAMS analysis for infrastructure asset managers is given by Rijkswaterstaat (2012) as reliability, availability, maintainability, safety, security, environment, economics, health and politics (Ramssheep). Various studies have evaluated the effectiveness of the Ramssheep approach as well as commented on the ability to quantify values for each of the indicators (Litherland *et al*., 2019; Wagner, 2012; Wagner and Van Gelder, 2013). An alternative structure was proposed by Karim *et al*. (2015), named Ram4S (reliability, availability, maintainability, safety, security, sustainability and supportability). These existing studies highlight the advantages of extending the RAMS framework. The objective of this research is to introduce and formalise further an ExRAMS analysis for specific use on railway networks.

Benchmarking and comparing between railways has always been considered a desirable objective for railway IMs. The Platform of Railway Infrastructure Managers in Europe (Prime) European framework (Prime, 2018a, 2018b) is a recent example of developments in this area.

ExRams parameters

The ExRAMS framework contains ten parameters based on the parameters defined by Litherland *et al*. (2019). The ten parameters were organised in a four-level hierarchy, as shown in Figure 1. The parameter structure is based on BS EN 50126 (BSI, 2017). The bottom level of the hierarchy considers ‘asset condition’. Two metrics are considered to assess the asset condition: ‘condition and remaining life’ and ‘utilisation’. The third level of the hierarchy, ‘asset performance’, is as in BS EN 50126 and contains ‘reliability’ and ‘maintainability’. The second level of the hierarchy, ‘service performance’, considers the ‘environment’ and ‘train performance’ in addition to ‘safety’ and ‘availability’. There is a direct link between levels 2, 3 and 4 of the hierarchy; asset condition will directly affect asset performance, which in turn influences service performance. The top level of the hierarchy, ‘service offering’, contains two high-level metrics for assessing performance: ‘capacity’ and ‘capability and journey time’. These values are related, yet not directly influenced by the factors below, but are critical to railway performance and are normally set at the design stage or when a franchise is issued. As the parameters are all closely connected, when performing analysis with the ExRAMS framework, it is essential that all parameters are considered; considering one parameter alone could lead to false conclusions being drawn.

The area of ExRAMS is a rapidly developing area, and the metrics identified are under constant review, and it is possible that some asset managers may have other particular parameters that they wish to consider, which may not be completely considered within ExRAMS. An example is ambience and accessibility; no standard means of assessing these parameters, from the data currently available, could be found. It was therefore decided not to include these within the framework, as their inclusion would lead to individuals using their own assessment metrics, thus defeating the main purpose of ExRAMS: having a consistent approach across industry. The ten parameters selected, at the time of writing, are quantitatively the most well defined (see the section headed ‘The ExRAMS framework’), and there are sufficient data available to calculate them (see Litherland *et al*., 2021). It is possible in the future as more parameters become well defined that the framework will be updated to include them; however, the base ten parameters must remain unchanged.

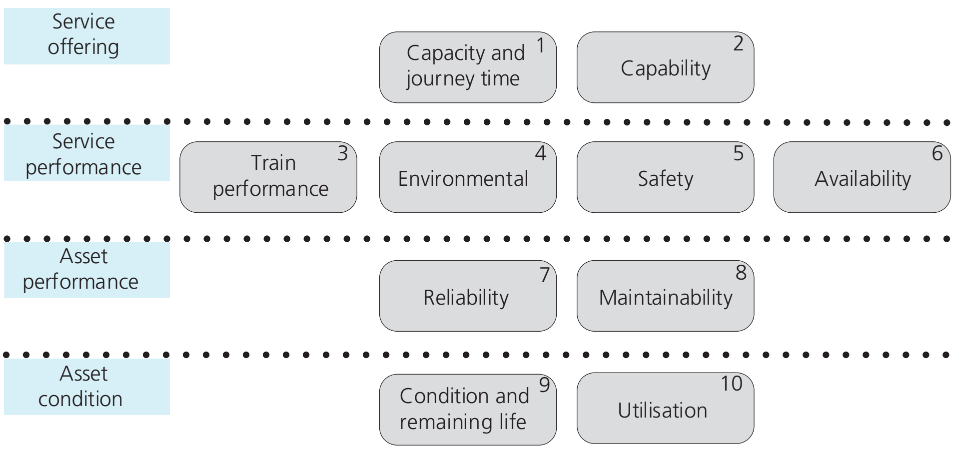

Figure 1. ExRAMS framework

The ExRAMS framework

This section provides a definition of each of the ten parameters within the ExRAMS framework and a means to calculate a number of metrics to assess them. A range of sources was reviewed in order to define the parameters considered in this study. The sources were reviewed in a hierarchical manner: international standards were considered in the first instance; following this, EU frameworks were consulted; and finally, textbook and industry definitions were used.

Capacity

Capacity is focused on the maximum possible throughput of trains on a given section of the network and is impacted by a large range of factors, including track layout and the signalling system. The subject of railway capacity regularly appears in literature. However, '[w]hilst the term railway capacity is used frequently, it has neither a standard definition nor a standard method of measurement' (Roberts *et al*., 2011: p. 1).

One of the broadest definitions of capacity, given by the International Union of Railways, is 'the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the IM's own assumptions; in nodes, individual lines or part of the network with market-oriented quality' (UIC, 2004: p. 3). Other definitions for theoretical and practical capacity were proposed by Krueger (1999). A theoretical sectional running time calculation was proposed by Kozan and Burdett (2005) to model capacity and investigate the phenomena that affect it. Assad (1980) investigated how delays impacted capacity and performance. Capacity in terms of signalling performance was also investigated by Woodland (2004).

Closely linked to capacity is utilisation. As discussed, capacity is focused on the maximum possible throughput of trains; utilisation is an assessment of how much of this maximum is being used. Network Rail assesses utilisation using the capacity utilisation index (CUI). The CUI currently measures the utilisation of track sections only and does not consider junctions (Roberts *et al*., 2011). It can be calculated according to

$$\text{CUI} = \frac{A+B+C}{A+B+C+D} \times 100 \qquad (1)$$

where A is the occupied (used) capacity, B is the unusable capacity, C is a recovery allowance and D is the unused capacity.

The route capacity is normally limited by certain network attributes such as

- number of running lines
- junctions
- signal separation
- sidings/loops
- number of platforms.

Railway signalling can be divided into two types: fixed-block (conventional) and moving-block signalling systems. In a moving-block signalling system such as the European Train Control System, the positions of all trains are known and the train separation is limited only by the braking distance of the trains and capacity is maximised (Theeg and Vlasenko, 2009) Nonetheless, in a fixed-block signalling system, which is still the most common worldwide and has been used extensively since the 1800s (Durmus *et al*., 2016), the signalling layout significantly influences capacity. Therefore, the capacity metric in this paper is based on a fixed-block signalling system.

In basic terms, when using a fixed-block signalling system, once a train passes a signal, any preceding trains cannot pass that signal until the first train exits the block. The time between a train entering and leaving a block is dependent on factors such as the length of the block and the train speed. Five factors were considered when calculating the time to travel between signals:

- distance between signals
- maximum line speed
- line speed changes
- station locations
- number of signal aspects.

Figure 2 shows an example route and how the theoretical maximum capacity can be determined based on the signalling layout. In the example, all the signals have three aspects (clear, approach/caution and danger/stop). There is one line speed change on the route (between signals 2 and 3) and one station (between signals 3 and 4). The minimum time to travel between

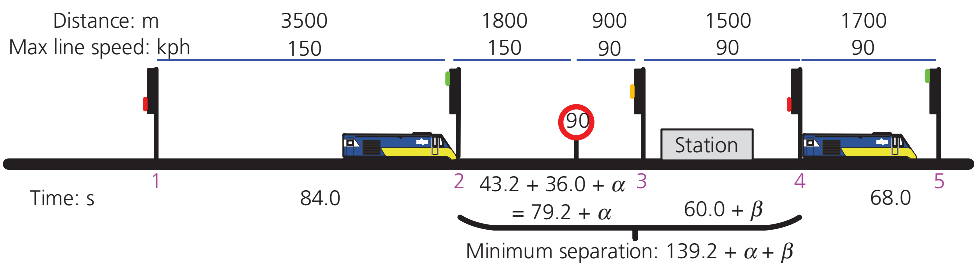

Figure 2. Capacity calculation

two signals is calculated based on the distance and maximum line speed. An extra factor α is added for any change in line speed, as trains have a slow acceleration rate and so the time taken to adjust speed needs to be considered. β seconds are also added for every station between the signals. In the example, the distance between signals 3 and 4 is 1500 m, the line speed is 90 km/h and there is one station. Therefore, the minimum time required to travel between signals 3 and 4 is 60 + β seconds. It is assumed that trains must be a minimum of two full blocks apart to allow running at line speed. In Figure 2, the first train has just passed signal 4. Therefore, the second train must be at least 139.2 + α + β seconds behind to ensure that signal 2 shows a clear aspect when the second train reaches it (as shown in Figure 2); this time is defined as the minimum separation time. If the second train is less than 139.2 + α + β seconds behind the first (less than the minimum separation time), then signal 2 will show an approach aspect when the second train reaches it, and the train will have to slow down ready to stop at signal 3 if required.

To assess the capacity of the route, the minimum separation time can be converted into the maximum number of trains per hour, τ, using

$$2. \quad \tau = \frac{3600}{\mathrm{MST}}$$

where MST is the minimum separation time in seconds. The area with the largest minimum separation time and hence the least number of trains per hour is assumed to determine the capacity of the route.

Capability and journey time

The capability of a railway can be assessed based on attributes of the network; the attributes of interest will vary between different stakeholders and different asset managers. Prime (2018b: p. 23) states that '[a]sset capability describes the functionality of the IM's railway network. It provides the overview of the capability of the network and specifically the extent to which the network meets the TEN-T [Trans-European Transport Network (EC, 2019)] requirements'. In the ExRAMS framework, functionality and hence capability are assessed based on five network attributes.

- Maximum permitted axle load. The minimum, lower quartile, mean, medium, upper quartile and maximum of the maximum permitted axle load, in tonnes, are expressed within this metric. The values were calculated based on the frequency to take into account the length of the section. The most important value is the minimum, as this will fundamentally limit the type (weight) of train that can operate on the route. The difference between the minimum and lower quartile is also important, as this highlights how easy it would be to increase the maximum permitted axle load on the route.
- Maximum permitted line speed. The minimum, lower quartile, mean, medium, upper quartile and maximum of the line speed across the route, in miles per hour, are expressed within the metric. The minimum is expressed, as this is the limiting factor for the journey time between stations. Considering the maximum is also important to ensure that trains with greater speed capabilities are not restricted by slower trains. The journey time was considered within this parameter, as line speed is thought to be the main limiting factor for journey time.
- Electrification classification. In the UK network, there are six broad types of electrification classification: no electrification (diesel trains only), alternating-current overhead line equipment (OLE), direct-current OLE, third rail, fourth rail or some combination of the these. The electrification metric records the percentage of each type of electrification.
- Loading gauge. The loading gauge describes the shape and size of trains that are permitted to use the route. A list of UK loading gauges can be found at the website of the Rail Safety and Standards Board (RSSB, 2015). The metric for loading gauge in this study focuses on freight loading gauge (W loading gauge). For each of the eight W gauges, the route is given a yes, 'Y', if permitted for the whole route and a no, 'N', if not permitted. Restricted running, 'R', means that there are some restrictions on that gauge – for example, not permitted on certain platforms.
- The European Rail Traffic Management System (ERTMS). The final parameter considered is ERTMS (2018). The percentage of the route currently under ERTMS control is expressed alongside the Prime (2018b: p. 24) metric '[i]n 2030, the percentage of main track-km planned to have been deployed with ERTMS'.

Train performance

Train performance is one of the most critical metrics to customers and is regularly used to assess the performance of rail companies. Indeed in the UK, the new Emergency Recovery Measures Agreements issued in response to the coronavirus pandemic include performance as a key metric. According to Prime (2018b), train performance is made up of punctuality and robustness. Punctuality is an assessment of how many trains are 'on time' and aims to measure the number of trains that are late and the extent to which they are late. Robustness assesses the ability of the system to cope with failures.

Punctuality

From the point of view of a train operator, there are two main parts to train punctuality, how on time the trains are and the size of the penalty cost that they have to pay to customers and other train operators due to their delays. There is a range of difference performance measures used across the rail industry. In the UK, Network Rail assesses train punctuality using a range of different measures, including

- performance minutes comprised on actual minutes lateness and deemed minutes lateness
- on-time measures
- legacy measures such as public performance measure (PPM) and the number of trains that are cancelled and significantly late (CaSL) (ORR, 2019a).

PPM is defined as '[t]he percentage of scheduled trains which successfully run their entire planned route, calling at all timetabled stations, and arrive at their terminating station "on time", where "on time" means within five minutes of the scheduled destination arrival time for London and South East and regional operators, or within ten minutes for long-distance operators' (ORR, 2019b: p. 2) and is a measure of how many trains are on time. CaSL is a measure of trains that are significantly late (arriving between 30 and 119 min late at their final destination) or cancelled.

A different approach is exhibited by Transport for London (TfL, 2018), which assesses train punctuality using lost customer hours and is calculated based on the number of delay minutes multiplied by the number of passengers on the train, whereas the Finnish Transport Infrastructure Agency (FTIA, 2019) assesses punctuality based on the number of trains that are more than 5 min late at their destination. This variation in metrics makes comparing train performance between different train operators difficult.

Robustness

The robustness of the system is a measure of how well the network responds to failures and is closely linked to reliability. For use in the ExRAMS framework, robustness is calculated based on the Prime (2018b: p. 15) metric '[a]verage delay minutes caused by asset failures on main track'. (A main track is a railway line maintained and operated for running trains.) The robustness metric was calculated by dividing the total number of delay minutes by the number of asset failures. To enable better comparison, it is suggested that asset failures be grouped by asset class.

Environment

It is generally accepted that rail transport is significantly 'greener' than road transport (Lalive *et al.*, 2018; Schmutzler, 2011). Analysis performed by Energy Saving Trust (EST, 2018) suggests that on a journey between London and Edinburgh, the carbon dioxide emissions when travelling by train are around four times less than by car and around five times less than by aeroplane (see Figure 3). For any new rail projects or major upgrade works, such as High Speed 2, the environmental impact forms a fundamental part of the business case.

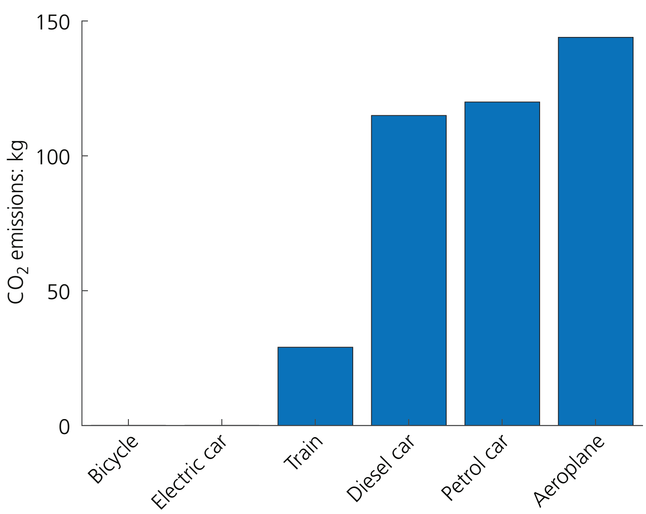

Figure 3. Carbon dioxide emissions produced on a journey from London to Edinburgh. Note: for electric cars, tailpipe emissions are zero. The original source of electricity emissions will vary (EST, 2018)

Nevertheless, it is difficult to assess quantitatively the overall environmental performance of the railway, particularly for electric traction, as, similar to electric cars, the emission of the electricity source can be variable and unknown. Furthermore, the environmental impact of maintenance and repairs to the railway is often not considered in emission calculations, and for some of the heavy machinery required to perform these tasks, their emissions are not insignificant.

Additionally, although the overall environmental performance of rail transportation is superior to that of other transport industries, some areas of the railway sector can still cause environmental concerns. For example, the level of air pollution in major enclosed (under canopy) stations can be significantly higher than recommended safety levels. The rail industry can also contribute significantly to noise pollution and soil pollution. Stojic *et al.* (2017) found that railway transport is a potential source of polychlorinated biphenyls and heavy-metal soil pollution.

There is currently no internationally recognised method for quantifying the environmental impact of the railway. The impact can be broken down into two types: the environmental impact under normal conditions and the environmental impact under abnormal conditions, such as during a derailment.

In the ExRAMS framework, only the impact under normal conditions will be considered. The desired metric for environmental performance would be the emissions (in terms of carbon dioxide and other gases) per passenger-kilometre. Nevertheless, calculating these figures is not a trivial task, as there is considerable uncertainty for train emissions per kilometre, passenger numbers and the emissions of non-train assets. At this stage in the ExRAMS framework, based on the assumption that electric trains emit less greenhouse gases than diesel trains, it is proposed that the environmental performance be assessed based on two metrics: diesel train-kilometres as a proportion of total train-kilometres and electric train-kilometres as a proportion of total train-kilometres, where total train-kilometres refer to both passenger and freight trains under all traction types. These data are readily available to railway asset managers.

Safety

Safety can be defined as 'freedom from unacceptable risk' (IEC, 2013). A more specific railway definition is given by Prime (2018b: p. 10): '[s]afety is the primary focus of the management of a railway IM and a prerequisite in any framework of management indicators. It is the most important and essential element in the performance of an IM, and affects customers, stakeholders, the reputation of the IM, the railway and society at large. Safety should be considered with a holistic perspective, including as well the fundamental task of providing a stable, safe and secure network for the user and the IM's staff, wider aspects of safety such as suicide prevention and minimising trespass events'. There are a number of performance indicators that can be used to assess safety performance, including

- persons seriously injured and killed
- significant accidents
- suicides and attempted suicides
- workforce accidents.

In this study, the 118 hazardous events, including 'train striking or struck by an object (not resulting in derailment)' and 'collision between two passenger trains in the station (permissive working)', identified by the RSSB are considered within the safety parameter.

It is proposed that the consequence of each hazardous event be assessed in terms of the fatalities and weighted injuries (FWI) index. Within the FWI index, a fatality is given a score of 1, a major injury is given a score of 0.1 and a minor injury is given a score of 0.05. In the ExRAMS framework, safety is assessed as the expected number of FWI per year per kilometre.

Reliability

Reliability, maintainability and availability are closely related. The reliability is an assessment of how often failures occur. The more occurrences of failure of a component, the less reliable it is. Reliability can be defined mathematically as the probability that a component or system remains operational from time zero to some later time τ given that it was operational at time zero. It can be calculated using the following expression:

3. $$R(t) = \int_t^{\infty} f(x)\,\mathrm{d}x$$

where $f(x)$ is the probability density function of the distribution of failure times. The reliability of systems of components in series and parallel is also well documented (Elsayed, 2012).

However, in railway systems, many of the components are not independent; hence, determining $f(x)$ analytically is often not possible. Additionally, there are a large number of interdependent series and parallel components; hence, calculating reliability in the traditional sense is not practical. Therefore, when railway asset managers describe the reliability of their system, they generally use a range of metrics, none of which is based on the mathematical definition given in Equation 3. This study presents two metrics that can be used to assess the reliability of a railway system:

- number of service-affecting failures (SAFs)
- mean time between SAFs.

To calculate these values two assumptions were made.

- Only SAFs (faults that cause delay minutes) are considered.
- All SAFS are considered to happen at independent times.

Maintainability

Maintainability is an assessment of how expeditiously a component can be repaired following a failure. For a component that fails regularly, it is generally required that it can be fixed quickly to minimise disruption to service. However, for highly reliable components, it can be acceptable to have a longer repair time. Maintainability is mathematically defined as: the probability that the component or system will be restored to a fully operational condition within a specified period of time and is often approximated according to

4. $$M(t) = 1 - \mathrm{e}^{-t/\mathrm{MTTR}}$$

where $M(t)$ is the probability that the component is repaired within time t and MTTR is the mean time to repair (Andrews and Moss, 2002).

The primary benefit for asset managers conducting a maintainability analysis is that it allows them to deduce how long it takes to finish various maintenance tasks. This performance can be compared with past maintenance performance, as well as the performance of other railway operators. Figure 4 shows the various stages of planned and unplanned maintenance. If IMs have an enhanced understanding of

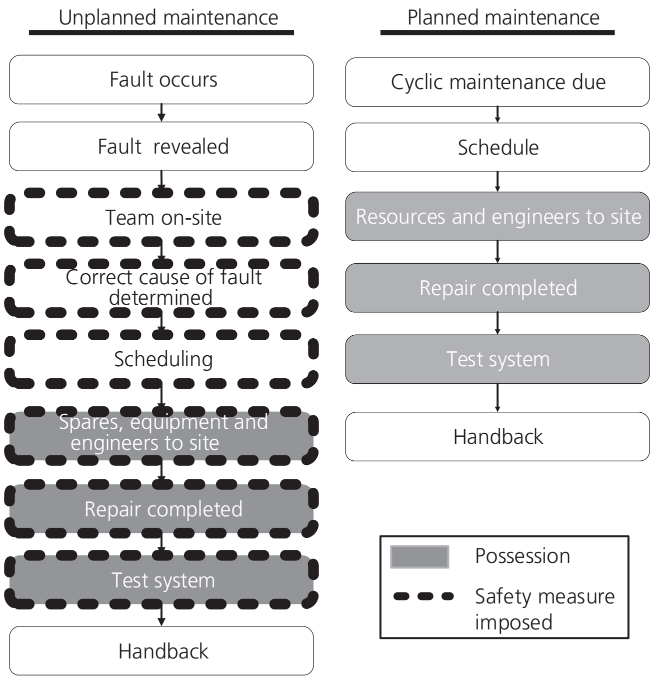

Figure 4. Maintenance tasks during unplanned and planned maintenance

the individual parts of the maintenance process, they can make more informed decisions and streamline the maintenance process.

Nonetheless, for railway networks, it can be difficult to calculate the maintainability using standard techniques such as the method shown in Equation 4, as the condition of many railway assets is not described by two condition states and maintenance scheduling is often based on the time when engineers can obtain access to the track. During possessions, when engineers are granted access to the track, they are likely to group maintenance tasks together and undertake a significant volume of work.

In the ExRAMS framework, it is proposed to assess maintainability based on the total number of hours of maintenance work completed and the volume of work done, broken down into the sub-tasks listed in Figure 4.

Availability

In an engineering sense, availability can be defined as 'the fraction of the total time that a component or system is able to perform its required function' (Andrews and Moss, 2002: p. 5). Furthermore, in a traditional RAMS analysis, it is calculated based on the mean time to failure (MTTF) determined from the reliability and MTTR determined from the maintainability according to

5. $$\text{availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$$

This metric is well suited to systems where the system state is binary (working or failed) and the effect of component/asset failure on the system is well understood. As discussed in railway networks, neither of these phenomena is true. It is therefore proposed to assess the availability based on 'possessions'. Possessions are periods of time where a route is closed to traffic to allow maintenance work to take place. For use in the ExRAMS framework, it was decided to group possessions into five categories based on length of time spent and when they occur:

- night possession: possessions that are less than 8 h and are assumed to have taken place in just one night
- weekend possession: possessions that are more than 8 h and less than 56 h and fall within the following time frame: 22:00 Friday to 06:00 Monday
- working day possession: possessions that are more than 8 h and less than 56 h and fall within the following time frame: 06:00 Monday to 22:00 Friday, excluding any bank holidays and public holidays
- bank holiday possession: bank holiday possessions with up to an additional 24 h on top of a regular weekend possession (56–80 h)
- extended possession: possessions that may occur during national holidays when there are a number of bank holidays in a row (more than 80 h).

The availability can then be assessed according to three metrics:

(*a*) percentage of total working days that a possession is not taking place
(*b*) percentage of total weekends that a possession is not taking place (there are assumed to be a total of 52 weekends in a year)
(*c*) percentage of total nights that a possession is not taking place (there are assumed to be 365 nights per year).

Type (*a*) is assumed to be the most critical, as possessions during a workday are the most disruptive to traffic. However, there is an increasing demand for services during weekends and bank holidays, so the impact of all possession categories must be considered.

Condition and remaining life

An asset-management plan should contain asset data held for both financial and non-financial purposes, including replacement value and remaining useful life (BSI, 2018). The estimation of the remaining useful life of components is at the centre of system prognostics and health management. It allows asset managers to make informed decisions based on the time left until functionality is lost (Saha *et al*., 2009). There is a wide range of techniques that can be used to model remaining life; these can be grouped into three main areas (Chen *et al*., 2011):

- model-based approaches
- fusion-based approaches
- data-driven approaches.

The service life of concrete sleepers was investigated by Kaewunruen *et al*. (2016). Gebraeel and Lawley (2008) proposed using neural networks to model the degradation and compute the continuously updating residual life distributions of partially degraded bearings. Service life estimation has also been used to predict the remaining life of batteries (Saha *et al*., 2009).

Remaining life can be defined as the 'remaining time before system health falls below a defined failure threshold' (IEC, 2015). It is critical that railway IMs understand the condition of their assets and the time until the asset will need replacing (remaining life). This comprehension of the system is vital when developing maintenance strategies.

The condition assessment method varies significantly between railway operators and across asset classes. Due to the large variation in condition assessment between assets and between rail operators, to obtain a comparable metric for benchmarking, it is proposed that condition metrics be expressed in terms of monetary value. Consequently, in the ExRAMS framework, it is proposed to assess condition and remaining life according to the following three metrics:

- the replacement value of the assets
- estimate of the residual (current value) of assets
- the percentage difference between the replacement value and the residual value.

Notwithstanding, there is still some subjectivity in the value assigned to assets.

Utilisation

Utilisation and capacity are closely linked, and like capacity, there is no agreement on a definition of utilisation. Prime (2018b: p. 23) assesses utilisation based on the degree of utilisation of passenger trains, defined as '[a]verage daily passenger train-km on main track (revenue service only, no shunting, and no work trains) related to main track-km'.

Capacity focuses on the theoretical maximum amount of trains that can run on the network. Utilisation can be used as a means of expressing the proportion of the capacity that is currently being used. It is proposed to assess utilisation based on the current number of trains that use the route of interest.

Conclusion

The implementation of a RAMS analysis for railway networks using the traditional mathematical definitions of RAMS is a difficult task and often an intractable problem. Consequently, each railway asset manager currently has their own implementation of RAMS, which makes comparing between RAMS analyses impossible. This paper presents an ExRAMS framework defined specifically for railway infrastructures. The framework is designed to consolidate the various approaches to RAMS in the railway industry into one single approach that can fulfil the needs of all railway IMs. The framework presents ten parameters in a four-level hierarchy to assess RAMS performance.

For each parameter, a range of metrics was determined from the traditional definition and a range of international standards. The definitions were designed to be as general as possible and not dependent on network-specific data. The one metric where a network-specific measure was still required was the assessment of train punctuality, as each railway operator uses a different measurement technique. This paper presents methodologies to calculate each of the metrics.

It is perceived that by having a comprehensive RAMS framework, which has demonstrated its effectiveness on the UK network, a wider range of IMs will use the proposed framework in the future rather than their own bespoke approach. The intended outcome of this study is to enable enhanced comparisons between routes and provide insight into why some routes perform differently. Additionally, having an extensive understanding of the current functional status of assets should facilitate more refined predictions of their future operation. In future studies, the framework can serve as the basis for the development of prediction and optimisation tools for railway asset managers. To enable further development of the framework, analysis should be undertaken to understand the interactions between the different parameters in the framework. Any analysis should explore the impact of the alteration of one parameter on the other parameters.

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