Development of an Extended RAMS Framework for Railway Networks

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Railway asset managers have finite resources which requires them to make strategic decisions on where, when and how the available budget will be spent on the railway, while ensuring safety limits are maintained and a high level of performance is delivered for customers. The purpose of this research is to develop a suitable framework, which can be used by railway asset managers, to quantify asset performance in a way that enables comparisons between different parts of the railway and enables the asset manager to make key decisions on how the railway can be improved. A frequently used assessment tool is RAMS (Reliability, Availability, Maintainability and Safety) analysis. In recent years RAMS analysis has been extended to include additional parameters such as: security, health, environment, economics and politics (SHE€P). This research proposes an extended RAMS framework, which considers 12 parameters in a four level hierarchy, specifically for use on railway networks by railway asset managers.

Keywords: Asset Management, Performance, Railway, RAMS, RAMSSHE€P.

1. Introduction

This paper proposes a new assessment framework for railway asset managers. It is an extension of RAMS (Reliability, Maintainability, Availability and Safety) analysis. It provides a means of assessing the network, identifying areas which are performing differently and potentially allow comparison between different railway networks. The framework allows asset managers to make decisions regarding design, maintenance and operation of the railway.

RAMS analysis is a well-established framework used to assess a system or component. RAMS analysis is well suited to systems where the failure modes are well understood. However, in railway systems, while failure modes tend to be well known due to a long history of operation, the consequences of a given failure can be very different depending on the part of the network in which it occurs. The aim of this paper is to apply RAMS analysis to railway networks and explore how traditional RAMS analysis can be adapted for use in the railway industry. This paper aims to, as much as possible, use International Standards to define terms. However, for a number of the additional parameters considered no internationally recognized definition exists, for these parameters this paper presents a novel means to calculate them.

2. The Evolution of RAMS

The earliest examples of Reliability, Maintainability, Availability (RAM) analysis can be found in the nuclear industry, Cleveland et al. (1985). Further examples of RAM analysis can be found in the aerospace industry, Cole (1998), plant industry, Rotab Khan and Zohrul Kabir (1995), and telecoms industry, Hamersma and Chodos (1992). In some early case studies it was referred to as ARM.

In the nuclear industry, safety studies were performed as early as the 1950s, Beckerley (1957), and by 1970 comprehensive safety reports were produced, US Nuclear Regulatory Commission (1975). Towards the end of the 20th century, following a spate of accidents such as Flixborough [1974], Three Mile Island [1975] and Chernobyl [1986], safety assessments were no longer performed by the industry but by independence safety bodies. This resulted in stricter safety guidelines and a desire to avoid similar accidents.

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),

Proceedings of the 29th European Safety and Reliability Conference.
Edited by Michael Beer and Enrico Zio

ISBN: 981-973-0000-00-0 :: doi: 10.3850/981-973-0000-00-0_esrel2019-paper

as opposed to the standard, safety (Zoeteman and Braaksma (2001); Breemer (2009)). However, there is now universal agreement in the '*S*' being safety; the industry standard for railway RAMS BS EN 50126 (British Standards Institution (2017)) recognizes the '*S*' as safety.

Although RAMS normally gives a complete picture of the system in some cases it may be necessary to consider additional parameters. Wagner and Van Gelder (2013) worked on expanding the traditional RAMS framework; RAMS was extended to RAMSSHE, RAMS+ security health and environment, and finally RAMSSHE€P (RAMSSHE+ economics and politics). This paper aims to introduce an alternative extension of a RAMS framework, for specific use on railway networks.

3. Preferred Subset of Parameters

Upon review it became apparent that the RAMSSHE€P framework does not provide a complete assessment of a railway network. Therefore in this research an extended framework consisting of 12 parameters, organized in a four level hierarchy is presented as shown in Figure 2.

As RAM parameters are integral to system performance they will be considered in the analysis. '*Safety*' will also be considered as it is fundamental to any railway network. Currently the data on the UK network does not fully support a RAMSSHE€P analysis, at this stage the only SHE€P parameter considered directly is '*Environment*'. The environmental impact is considered due to the importance of climate change and green energy; currently train travel is one of the most low carbon means to transport people and goods (International Energy Agency (2009)).

'*Security*' will not be considered as a parameter in its own right. However, delay minutes that can be attributed to security incidents will be considered in train performance. '*Health*' will not be considered at this stage, as it is unclear how health performance can be measured and there is insufficient data. '*Economics*' will not be considered at this stage, as to fully quantify economics a life-cycle cost (LCC) analysis is needed and this is, currently, beyond the scope of this study. '*Politics*' is not considered as currently it is impossible to define in any meaningful way the political performance of the railway.

It was concluded that RAMSE parameters alone were not sufficient to give asset managers a complete picture of the railway. Therefore, seven additional parameters were added to create a framework consisting of 12 parameters in a four level hierarchy as shown in Figure 2. The parameters were organized in a hierarchical structure based on the International Standard BS EN 50126 (see Figure 1). The hierarchy was increased from three to four levels. The bottom level of the hierarchy '*Asset Condition*' considers the factors that influence '*Reliability*' and '*Maintainability*'. Three metrics are considered to assess the '*Asset Condition*'; '*Condition*', '*Remaining Life*' and '*Utilization*'. The third level of the hierarchy '*Asset Performance*' is as in BS EN 50126. The second level of the hierarchy, '*Service Performance*', considers the '*Environment*' and '*Train Performance*' in addition to '*Safety* and '*Availability*'. There is a directly flow between levels two, three and four of the hierarchy; '*Asset Condition*' will directly effect '*Asset Performance*' which in turn influences '*Service Performance*'.

The top level of the hierarchy '*Service Offering*' contains three high level metrics to assess performance; '*Capacity*', '*Journey Time*' and '*Capability*'. These values are 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.

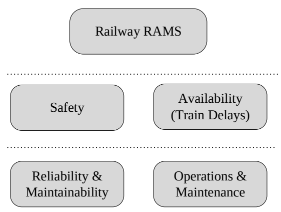

Figure 1. Interaction between reliability, availability, maintenance and safety (British Standards Institution (2017))

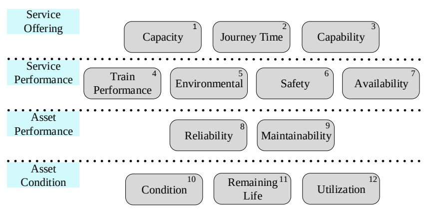

Figure 2. Extended RAMS Framework

4. Defining Parameters

A range of sources were reviewed in order to define the parameters considered in this study. The sources were reviewed in a hierarchical manner; International Standards were considered first, EU frameworks were reviewed next, and then textbook definitions and finally Network Rail (NR) definitions were used. When defining parameters International Standards and the PRIME (Platform of Railway Infrastructure Manager in Europe) European framework (PRIME (2018a,b)) were sufficient to provide quantification. However when applied to railway networks the calculation procedures given in International Standards and PRIME were not always sufficient. Therefore, to calculate these parameters, textbook definitions and NR definitions were also consulted. The 12 parameters are defined as:

- **Capacity**: There are a range of definitions for capacity in International Standards however none are specific to railway networks and defining the capacity of a railway is nontrivial. PRIME (2018b) assesses capacity based on a number of key indicators;

  (a) Possession and possession utilization
  (b) Time lost due to temporary and permanent speed restrictions
  (c) Congested tracks and congested nodes where congestion is defined according to Article 47(1) of Directive 2012/34/EU (European Commission (2012))

  In this study, capacity will be assessed based on (b) and (c), as possessions are more aligned with '*Availability*' and '*Maintainability*'. The existing definition of congestion of nodes is qualitative. To obtain a quantitative value, congestion will assessed by calculating the minimum time to travel between adjacent timing points. The largest value of these minima will be used to describe the capacity of the considered route.
- **Journey Time**: A journey can be defined as '*Movement of a person who is traveling between two locations*' (International Standards Organisation (2015b)). In this study locations will be stations and the journey time will be defined as the time taken to travel between two stations.
- **Capability**: There is no international definition of railway capability. PRIME (2018b) states that; '*Asset capability describes the functionality of the infrastructure manager's (IM) 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,European Commission (2019)) requirements*'.

  In this study, the capability will be assessed based on a range of factors that limit the number and/or type of trains that can run.
- **Train Performance**: Train performance is very railway specific. A range of metrics are used in the UK; at NR, public performance measure (PPM) and delay minutes are used. Whereas, at Transport for London, lost customer hours is the primary metric Transport for London (2018). In this study, performance will be defined according to PRIME (2018b), which states that, '*Performance is made up of punctuality and robustness*'

  (a) Train punctuality is defined as; '*the percentage of national and international passenger and freight trains (excluding works trains) which arrive at all strategic measuring points with less than or equal to five minutes delay*', where;
  (b) Robustness is defended as '*Average delay minutes caused by asset failures on main track according to UIC CODE 450-2, numbers 20-25 and 28-29*'.
- **Safety**: Safety is defined as; '*freedom from unacceptable risk*' (International Electrotechnical Commission (2013)) A more specific railway definition can be found in PRIME (2018b): '*Safety 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 as 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 minimizing trespass events*'. PRIME defines the following key performance indicators (KPIs) to assess the safety performance:

  (a) Significant accidents
  (b) Persons seriously injured and killed
  (c) Suicides and attempted suicides
  (d) Workforce safety
- **Environment**: There is no internationally recognized means to quantify the environmental impact of the railway. It is common practice to only consider the environmental impact and consequence of failures. This can be assessed as '*the number of environmental incidents*'. The majority of environmental incidents will be due to freight train spillages or derailments such as the incident in Stewarton, UK (Rail Accident Investigation Branch (RAIB) (2010)). The environmental impact of an operational railway is determined by a range of factors. PRIME (2018b) proposes assessing the rolling stock traction type[a]:

  (i) '*Total diesel train kilometers operated.*'
  (ii) '*Total electric train kilometers operated.*'

  Asset managers have little control over the operational environmental impact of the railway. In this study, only 'the number of environmental incidents' will be considered as these are more directly influenced by asset management decisions.
- **Reliability**: The reliability (of an item) is defined as; '*ability to perform as required, without failure, for a given time interval, under given conditions*' (International Electrotechnical Commission (2015)).

[a]Revenue services and shunting operations to and from depots and IM's working traffic.

- **Availability**: The availability (of an item) is defined as; '*ability to be in a state to perform as required*' (International Electrotechnical Commission (2015)).
- **Maintainability**: The maintainability (of an item) is defined as; '*ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance*' (International Electrotechnical Commission (2015)).
- **Condition**: Assessing the condition of a railway network can be difficult, there is no internationally recognized definition of condition. The condition is often assessed based on the normal condition '*Condition in which all means for project against hazards are intact*' (International Standards Organisation (2011)). However in railway networks the condition of railway assets is usually determined based on a condition index. In the UK, NR uses BCMI (Bridge Condition Marking Index) and TCMI (Tunnel Condition Marking Index) (Network Rail Standards (2009)) to assess the condition of bridges and tunnels, the condition index is also used to determine the remaining life of assets. PRIME assesses asset condition based on the number of asset failures subdivided into the following asset groups;
  (a) Signalling
  (b) Telecom
  (c) Power Supply
  (d) Track
  (e) Structure
  (f) Other

  and the total number of permanent and temporary speed restrictions (PRIME (2018a)).
- **Remaining Life**: Another useful measure of asset condition is remaining life defined as;'*remaining time before system health falls below a defined failure threshold*' (International Standards Organisation (2015a)).
- **Utilization**: A final measure of asset condition is utilization. There is no internationally recognized definition of railway utilization. PRIME assesses utilization based on; degree of utilization of passenger trains, defined as; '*Average daily passenger train-km on main track (revenue service only, no shunting, and no work trains) related to main track- km*' PRIME (2018a). In the UK, NR assesses the volume of traffic according to EMGTPA (Equivalent million gross tonnes per annum), this is an alternative measure of utilization.

5. Calculating Parameters

The following sections will explore how the parameters are calculated based on the definitions in the previous section. The '*Capacity*', '*Journey time*' and '*Capability* are generally decided in the design stage or when a new franchise is issued, these values tend to remain constant unless a major enhancement project is undertaken. These metrics will be assessed based on the adherence to these targets. The remaining parameters will be monitored in real time and used to assess the current performance of the network.

5.1. *Capacity*

There is no standard way to calculate the capacity of a railway network. The route capacity is normally limited by certain network attributes such as;

(i) Number of Running Lines
(ii) Junctions
(iii) Signal Separation
(iv) Sidings/Loops
(v) Number of Platforms

In this research the capacity will be calculated based on the time to travel between timing points. The minimum possible time to travel between timing points will be calculated as,

$$t = \frac{D}{S}, \tag{1}$$

where *D* is the distance between the timing points and *S* is the line speed. The capacity will be assessed as the maximum, of the minimum time between timing points, for a given route section.

Figure 3 shows an example route consisting of six nodes, the distance in meters and speed limit in kph between each node is shown. It can be seen that the maximum time of 38 seconds, occurs between timing points four and five. This section will cause bottlenecks, the capacity of the route is indicated by this value.

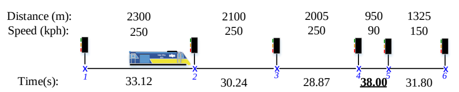

Figure 3. Example route section for capacity calculation

5.2. *Journey Time*

In this study, the journey time will be assessed based on the journey time index, *J*. Which will be calculated as,

$$J = \alpha \cdot \frac{A}{N}, \tag{2}$$

where A is the average timetabled time to travel between the two stations of interest, N is the distance between the two stations and α is a scaling factor based on the number of passengers that use the route. In this study α is chosen based on NR's route criticality. In the future it is hoped that a more universal definition of α can be determined.

5.3. *Capability*

In this study capability will be determined based on the six factors given in PRIME (2018b)

(i) Axle Load
(ii) Gauge
(iii) Line Speed
(iv) Train Length
(v) Electrification
(vi) Extent of ERTMS (European Rail Traffic Management System)

These values can be used to compare between routes, and can be used to determine assets that limit capability.

5.4. *Train Performance*

There is currently no standard way of calculating train performance on the railway. In this study punctuality will be assessed using the NR's PPM metric, which is defined as; '*The 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*' (Network Rail (2017)).

Robustness will be calculated as defined in PRIME, as delay minutes per asset failure. The asset failures can be categorized into the same asset groups listed under condition in Section 4. Moreover, an additional category could be included for delay minutes caused by security incidents.

5.5. *Safety*

There is no standard definition of safety on the railway, so defining a metric is difficult. There are a range of direct and indirect safety elements to be encapsulated in the safety metric. A common measure of safety performance on the UK railway is Fatalities and Weighted Injuries (FWI). However, fatalities on the railway are extremely rare, in 2016-17 there were 15 passenger fatalities on the UK railway network, of which seven were due to a tram derailment (Office of Road and Rail (2017)). As these events are so infrequent accurately predicting them can be difficult. Accident precursors, Kyriakidis et al. (2012), are a commonly used means of assessing railway safety risk. For example, the '*Top Event*' derailment will be influenced by a number of precursors such as; signal passed at danger (SPAD), signal failure or broken rail. NR and the Rail Safety and Standards Board (RSSB) have developed the '*Safety Risk Model*' and '*Precursor Indicator Model*' to calculate the probability of '*Top Event*' and the subsequent number of injuries and fatalities. These models will be used to assess the safety performance of the network in this study.

Another consideration in a safety metric is suicides. In 2016/17 there were 237 suicides on the overground rail network in the UK. Unfortunately suicide prevention is influenced by factors largely outside the control of asset managers. Nonetheless some measures such as; platform edge doors and additional fencing can be implemented to reduce suicide risk. However significantly reducing suicides requires long term strategies to reduce the underlying causes, to this end NR are working closely with the Samaritans. As suicides are largely out of the asset manager's control they will not be considered in this study.

5.6. *Environment*

There is no standard way of calculating the environmental impact of the railway. In this study the environmental performance will be assessed according to the '*number of rail related environmental incidents with major and significant impact or effect*' (PRIME (2018b)).

5.7. *Reliability*

The reliability of a component is well defined and can be calculated mathematically using the failure/hazard rate, $\lambda(t)$ (Andrews and Moss (2002)). It can be shown that the failure rate is related to the reliability according to the following equation;

$$R(t) = e^{-\int_0^t \lambda(\tau) d\tau}. \tag{3}$$

If the failure rate is constant the reliability is calculated as;

$$R(t) = e^{-\lambda t}. \tag{4}$$

Alternatively, if the failure rate is thought to be non-constant, a range of other distributions can be used to model reliability, including; Weibull, Gamma and Log-normal. If the component is repairable the Mean Time Between Failures (MTBF) can be expressed as,

$$\text{MTBF} = \frac{\text{Total Time} - \text{Total Down Time}}{n}, \tag{5}$$

where n is the number of failures. A railway network is made up of numerous components therefore reliability analysis needs to be extended to system level. The reliability of a system of components in series and parallel is well documented (Elsayed (2012)). If components are assumed to be independent the system reliability for n components in series can be calculated according to;

$$R^s_{sys}(t) = \prod_{i=1}^{n} R_i(t). \tag{6}$$

For n components in parallel, the system reliability can be calculated according to;

$$R^p_{sys}(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)). \quad (7)$$

In this study the reliability of a railway network is calculated based on the number of service affecting failures (SAFs) that occur. In this study SAFs are assumed to be;

(i) Independent
(ii) Cause complete failure of the system

If these two assumptions are made than the railway network can be modelled as a combination of assets in series with no redundancy and the reliability can be calculated using standard techniques according to Eq. 6. As the system is made up of many components in series it is difficult to achieve a high level of reliability on a railway network.

5.8. *Availability*

In a traditional RAMS analysis once the mean time to failure (MTTF) and mean time to repair (MTTR) have been calculated from the '*Reliability*' and '*Maintainability*', the '*Availability*' can be calculated as;

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}. \quad (8)$$

However in this analysis as the maintainability has not been calculated in the standard way, Eq. 8 cannot be used. An alternative measure of availability is required for railway networks. The availability metric in this study will be; '*the percentage of time it is not possible to run a full service on the network*'. This can be calculated by summing downtime for all assets, this approach was used to determine predictions for Crossrail availability and performance (King and Gugala (2018)).

5.9. *Maintainability*

Maintainability is a measure of how easily a system can be repaired following a failure and how much downtime results from the failure. The more easily the system can be repaired, the faster such repairs may be carried out and hence the smaller the downtime. The calculation procedure for maintainability as given by Andrews and Moss (2002) is; '*The probability that a failed item is repaired in the time interval* $(0, t)$'. This definition can be difficult to apply to real world systems and maintainability is commonly approximated using the following expression (Barringer (1997));

$$M(t) = 1 - e^{\frac{-t}{\text{MTTR}}}. \quad (9)$$

Railway networks comprise many components each of which are maintained under different regimes. The downtime during the maintenance process is made up of a number of parts as shown in Figure 4. The maintenance process can be analyzed to determine which parts of the process contribute the largest amount of downtime. Hence, allowing asset managers to make decisions on how the downtime can be reduced. An example of this is; handbacks at full line speed without needing a period of running at reduced speed, the 100th high speed handover in the UK took place in December 2018 (Network Rail (2019)).

Unlike reliability, calculating the maintainability of a railway network using standard techniques generally is not possible. Therefore to express the maintainability of a railway network a non-standard means is required. In this study the maintainability will be expressed as the number of hours spent on each of the planned and unplanned maintenance tasks shown in Figure 4.

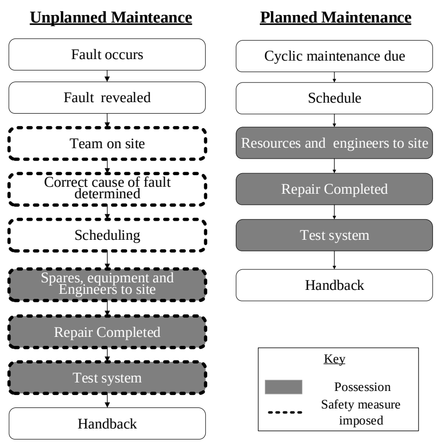

Figure 4. Maintenance actions during unplanned and planned processes.

5.10. *Condition*

NR assesses the condition of their assets using state based condition indexes such as BCMI and TCMI. In this study the asset condition was assessed based on NR condition indexes. The assets were grouped into the six categories defined by PRIME and listed in the '*Condition*' definition in Section 4.

5.11. *Remaining Life*

Remaining life is a common way to determine '*Asset Condition*'. The remaining life of assets is usually based on their condition. It is important to consider '*Remaining Life*' as it can have a significant impact on parameters higher up the hierarchy and needs to be taken into account when assessing the overall performance, as older assets would be expected to perform worse.

As discussed it is common practice to assess condition using a state based condition index. Figure 5 shows a simple four state condition index. For each state there is a deterioration rate, λ_i, these values can be used to determine the remaining life, *RL*, (the time to the '*failed*' (absorbing state)) according to;

$$RL = \sum_{i=1}^{d-n} \frac{1}{\lambda_{d-i}}, \tag{10}$$

where *d* is the total number of states (in the case of Figure 5, *d=4*) and *n* is the current number state of the asset. In the UK NR make assessments of the remaining life of all their assets based on condition indexes and engineering judgment.

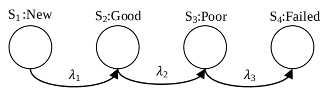

Figure 5. State based condition index

5.12. *Utilization*

It this study the passenger utilization, U_p, and freight utilization, F_p, was calculated according to the PRIME definitions:

$$U_p = \frac{\bar{P}}{L}, \tag{11}$$

$$U_f = \frac{\bar{F}}{L}, \tag{12}$$

where $\bar{P}$ is the average daily passenger train miles on main track (revenue service only, no shunting and no work trains), $\bar{F}$ is the average daily freight train miles on main track (revenue service only, no shunting and no work trains) and *L* is the length in kilometers of the given route.

6. Conclusion

This paper proposes an assessment tool for use by railway asset managers. The assessment framework proposed is an extension of a traditional RAMS analysis that considers eight additional parameters. The research established that reliability was the only parameter that could be calculated using traditional techniques. For each of the remaining parameters this paper presents a metric to calculate them based on EU frameworks and NR definitions. The methodology is being trialed on the TransPennine route, a major rail corridor in the north of England and, if successful, will be rolled out to other parts of the network. The framework is built as far as possible around internationally recognized standards and definitions. However, a number of parameters are calculated using UK specific metrics, which will be revisited in future work.

As future work, the authors would also like to undertake a LLC analysis to allow economics to be considered in the framework. Additionally there are likely to be dependencies between some of the metrics, once results are obtained from the TransPennine route it is hoped that these dependencies can be explored in more detail. The results from TransPennine will also be used to validate the assumptions made in the framework, to see if any revisions are required.

Acknowledgements

John Andrews is the Royal Academy of Engineering and Network Rail Professor of Infrastructure Asset Management. He is also Director of the Lloyd's Register Foundation (LRF) Resilience Engineering Research Group at the University of Nottingham. Jack Litherland is a Research Associate in Railway Infrastructure Asset Management. Gareth Calvert is conducting a research project funded by Network Rail and EPSRC grant reference EP/N50970X/1. Andy Kirwan is the Head of Advanced Analytics at Network Rail. They gratefully acknowledge the support of these organizations.

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