Risk-based maintenance planning for rail fastening systems

Kaewunruen, Sakdirat; Bin Osman, Mohd Haniff; Wong, Hao Cheng Eric

Risk-based maintenance planning for rail fastening systems

Sakdirat Kaewunruen, BE(Hons), MEng, Ph.D., MBA, MIEAust, CPEng, NER, RPEQ, FHEA.
Senior Lecturer in Railway and Civil Engineering, Birmingham Centre for Railway Research and Education, School of Engineering, University of Birmingham, B15 2TT, United Kingdom. ORCID: http://orcid.org/0000-0003-2153-3538. E-mail: s.kaewunruen@bham.ac.uk.

Mohd Haniff Osman, MSc.
Ph.D Student, School of Civil Engineering, University of Birmingham, B15 2TT, United Kingdom (corresponding author). ORCID: http://orcid.org/0000-0001-8255-9147. E-mail: mxo574@bham.ac.uk.

Mohd Haniff Osman, MSc.
Lecturer, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600, Malaysia. ORCID: http://orcid.org/0000-0001-8255-9147. E-mail: haniff68@ukm.edu.my.

Wong Hao Cheng Eric, MSc.
Engineer, Land Transport Authority of Singapore, 219428, Singapore. E-mail: not2worth@gmail.com.

Abstract

Failures in rail fasteners can lead to misalignments of the rails and even cause a train derailment. Current inspection and maintenance regimes for rail fasteners, however, do not adequately address the credible failure modes found in the field. In response to these improvement opportunities, a risk-based maintenance philosophy, driven by a risk management framework, is proposed for rail fasteners. The framework is primarily developed from ISO 31000 with underlying principles inferred from other applicable international standards. Reliability tools were then incorporated, allowing practitioners to arrive at an appropriate combination of reliability tools based on the circumstances under which the assessment is to be conducted. Monte Carlo simulations were undertaken on the imbedded anchors of rail fasteners to demonstrate how the resultant framework can be innovatively adopted in practice. The general findings highlight that accurate risk depiction is vital for track components (e.g. imbedded anchors, the failure modes of which are dependent on time), thereby, the timeframes at which risk for the component transits to different risk categories should be obtained. Note that the finding is unique to the example; thus, the proposed risk framework should be treated carefully before it is applied for other failure modes.

Keywords: rail fastener; rail failure; risk management; reliability analysis; inspection.

Introduction

Located at the interface between the rail and the sleeper (as depicted in Fig.1), the rail fastener maintains the vertical, lateral and longitudinal position of the rails relative to the sleepers. It also provides resilience to the rail-sleeper configuration so as to reduce the dynamic forces transferred from rails to the sleepers. For electrified railways, the rail fastener performs the additional function of providing electrical isolation between the rail and the sleepers.

Most fasteners today are elastic fasteners which typically embody an imbedded anchor, a clip or spring, an insulator, and a pad. Degradation in these components can ultimately lead to the inability of the fastener to execute the functions cited above. Proactively, a visual inspection is regularly performed which takes various types of patrols; routine walking patrols, detailed walking examination and detailed sleeper examinations (RailCorp Network 2013). However, the defects that the patrollers look out for in rail fasteners do not adequately address the generic failure modes. For instance, failure modes such as abrasion and high hydraulic pressures, which can lead to rail seat deterioration, are unable to be detected through visual inspection. The detection of rail seat deterioration would require the lifting of rail and removal of rail pad (Kernes et al. 2014).

As rail fasteners are intrinsically linked to the rest of the track system, having an inspection regime which does not identify defects at the failure modes brings the organization closer to serious incidents. In the case of rail seat deterioration, this means that the problem may only surface when there is a loss of rail cant or when there is gauge-widening. For records, rail fasteners have failed prematurely or deteriorated drastically within a short timeframe. A diode-grounded transit system which was designed to last for 35 years had to be replaced within seven years due to stray current corrosion (Barlo and Zdunek 1995) . Also, a rail corrosion defect in Sydney had deteriorated to five consecutive rail fasteners failures within a short span of three and a half years (The Office of Transport Safety Investigations 2014). Note that, elastic rail pads generally have a design life of 10 years. Without appropriate renewal of pads, those fastenings can be damaged faster. Nonetheless, unless a detailed investigation is triggered, the underlying failure modes may remain hidden until a serious incident presents itself. By then, the cost and resources required to address the failure mode may have become significantly higher.

In terms of resource allocation, inspection frequencies and mitigation priorities are currently determined by the expected and actual conditions of the rail fasteners. One would be to allow the frequency of inspection to depend on how aggressively the service has damaged the track. While reduction of inspection frequency is allowed, this is done ad hoc and is only permitted to a maximum of half (Network Rail 2009). Another would be to allow frequency of inspection and urgency of repair to depend, not only on how likely a serious incident can occur, but also on how serious that incident would be. For instance, though both may fall into the same track category, a line which runs high volumes of passenger service should be inspected and maintained more rigorously than a line which predominantly runs freight service because of the former's higher safety implications. Such optimization directs resources in accordance to risk criticality and not merely by the likelihood of risk.

In addressing abovementioned opportunities, a risk based maintenance approach is proposed for rail fasteners. Intuitively, each inspection or maintenance activity is treated as a risk control process intended to address a failure mode. This study concerns itself with the establishment of a risk management framework to ensure that risks remain relevant and accurate throughout the system lifecycle. In this regard, relevant international standards and reliability tools are embodied in a risk management framework. Overall, the proposed framework has features such as improves proactiveness of the inspection and maintenance regime for rail fasteners, further optimise resources allocation within the regime and improve the comprehensiveness of this regime.

Background study

Inspection on rail fastening system

In the UK, defects associated to rail fasteners are identified via foot patrols. The patrollers look out for the following defects in rail fasteners (Network Rail 2009):

i. Loose, missing, falling out and broken rail fasteners,
ii. Missing/displaced, expired and incorrectly fitted pads , and
iii. Broken/cracked and galled baseplates.

Frequency of foot patrols are determined by predefined track category, which is in turn determined by the speed of rail traffic and the equivalent tonnage of the line. Track categories range from Cat 1A, where speeds are high and equivalent tonnage are high, to Cat 6, where the converse is true. Frequency of basic visual inspection on plain line continuous welded rail, for instance, is weekly for Cat 1A track and once every four weeks for Cat 6 track, see Table 1for inspection frequencies for other track categories (Network Rail 2009, 2017).

Track inspection frequency is typically fixed but a review can be triggered by the engineer when there is a clear history of reliability issues such as poor track geometry, rolling contact fatigue or evidence of track bed failure. The extent to which frequency is increased predominantly lies on the engineer's judgement. On the other hand, when track condition has been found to be satisfactory, the engineer is able to reduce inspection frequency, but to a maximum of half. This review is normally driven by the need to optimize the patrolling regime or by difficulties in complying with the existing frequency. When a defect is found, response to rectify is not necessarily immediate. The urgency of response depends on how likely the defect can translate to an undesired event. For example, four missing or ineffective fastenings in a 60ft length of a Cat 1A track has a priority of M3 while the same phenomenon in a 60ft length of a Cat 6 track has a priority of M24 (Network Rail 2009, 2017). The former needs to be addressed within thirteen weeks while the latter has two years for resolution. This disparity is because the likelihood of an undesired consequence occurring is higher for the former than the latter.

In Australia, patrollers look out for similar rail fastening defects as that in the UK (RailCorp Network 2013);

i. Missing/corroded/over sprung/ineffective fastenings,
ii. Worn, incorrectly inserted or squeezed out insulators, and
iii. Severely worn pads which can be checked visually or with reference to gauge readings.

Inspection of rail fasteners is covered by various types of patrols. These are namely standard track patrols, detailed walking examination and detailed sleeper examinations. There is however very little variance in the frequencies. Standard track patrols and detailed walking examinations are fixed at twice a week and once in three months respectively for practically all track categories in the suburban mixed-traffic networks. Detailed sleeper examinations, on the other hand, are either annual or biennial depending on the sleeper type (RailCorp Network 2016).

Reliability tools

Failure mode, effects and criticality analysis

Failure mode, effects and criticality analysis (FMECA) is a systematic process to identify credible failure modes. According to (Quality—One International 2017), there are seven steps in developing an FMECA;

Step 1: FMECA pre-work and assemble the FMECA team

Step 2: Path 1 development (requirements through severity ranking)

Step 3: Path 2 development (potential causes and prevention controls through occurrence ranking)

Step 4: Path 3 development (testing and detection controls through detection ranking)

Step 5: Action priority & assignment

Step 6: Actions taken / design review

Step 7: Re-ranking risk criticality & closure

In Step 1, key documents, such as design, inspection and maintenance documents, are consolidated and an experienced multi-disciplinary team is formed to facilitate the analysis. In Path 1 development, the failure modes by which functions can fail and the associated effects of failures are identified. Each effect is assigned a severity ranking. After which, in Path 2 development, the causes associated with each failure mode are identified and the mitigation actions for each failure mode are formulated. Each cause is assigned an occurrence ranking. Path 3 development then adds detection controls such as real-time condition monitoring. Step 5 identifies the risk criticality for each failure mode based on its assigned occurrence and severity ranking and accordingly determines the priority of action for risk treatment. FMECA should be an evergreen process where risks and actions are regularly reviewed. Step 6 and 7 depicts this requirement.

Fault tree analysis

A fault tree analysis (FTA) is a top down failure analysis which analyses the failure of a system in terms of its contributory causes. In a fault tree diagram, the relationships between the causes and system failure are represented in terms of Boolean logic. The two main Boolean operators used are the OR and the AND gates. The OR gate is used under the situation that the output is TRUE when any one of the inputs is TRUE. The AND gate, on the other hand, is used under the situation that the output is only TRUE when all inputs are TRUE. If the probability values for all inputs are known, it would also be possible to calculate the probability of overall system failure using the Fault Tree Diagram.

Fuzzy probability analysis

When quantitative historical or comparative failure data are not available, risk analysis can be qualitatively conducted based on expert opinions. However, experts can diverge in opinions. In this regard, fuzzy probability analysis can be used to reduce the amount of subjectivity and uncertainty introduced from consolidating these opinions (Arunraj et al. 2013). As there are no standard rules that define how these can be selected, this makes fuzzy probability analysis inherently subjective. Nevertheless, if this tool is universally applied across all expert-based risk analyses in an organization, this consistent application reduces the overall subjectivity in such analyses.

The steps for conducting a fuzzy probability include expert weightages, membership functions, aggregation techniques and defuzzification. Initially, weighting factor, *w* is determined for each expert that will be involved in the risk analysis. This can be derived using criteria such as their years of experience and their job designations. The weighting factors for all experts involved should add up to 1. Following this, probability of a primary event at question is judged and expressed by the experts in linguistic terms which correspond to probability categories in the risk matrix. An example of how probability categories can be defined linguistically is as follows: 0.1 to 1 for 'A', 0.01 to 0.1 for 'B', 0.001 to 0.01 for 'C', 0.0001 to 0.001 for 'D' and <0.0001 for 'E'.

Step 3 presents numerous fuzzy membership functions can be used to represent the linguistic expressions, and the uncertainties and inaccuracies associated to these judgements. Out of which, trapezoidal fuzzy membership functions have been found to be one of the most practical (Duan et al. 2016). For the probability categories defined in Step 2, the corresponding trapezoidal membership functions can be as illustrated in Fig. 2 (Ahn and Chang 2016). Lastly, the aggregated fuzzy set Z is defuzzified into a fuzzy probability score, FPS. Techniques that can be used for defuzzification include centre of gravity, bisector of area, mean of maxima, leftmost maximum and rightmost maximum (Shi et al. 2014). The centre of gravity technique, for instance, uses the expression below to obtain the probability score.

Development of the framework

The following criteria have been defined for the development of the risk management framework. Firstly, the framework should be in compliant to relevant international standards. This is important as failure to do so may lead to incongruence with other frameworks that have been developed or will be developed. Secondly, the framework should provide guidance on what reliability tools can be adopted at each stage. In this section, standards and reliability tools have been analysed and incorporated to form the framework.

Standards

PAS 55:2008 – Asset management

The Publicly Available Specification for Asset Management 55-1:2008 and 55-2:2008 was first released in 2004. Under this specification, asset management has been defined as the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan (The Institute of Asset Management 2008). This definition contains concepts that depart distinctly from the traditional approach towards inspection and maintenance.

Firstly, asset management should not concern itself with just the management of assets but also the management of asset systems. In light of complex interactions between assets today, the macro perspective of assets is as important as the traditional minuscule approach. Failure of an asset may have far-reaching effects on the reliability of other assets. Conversely, these effects can be insignificant if the asset is redundant within the asset system.

Secondly, the standard advises that interventions should be planned based on their costs and the asset system's performance and risks. In this regard, preventive and even predictive maintenance, which advises the next course of action based on asset's condition and not risk, fall short on this requirement.

Lastly, the standard states that performance, risks and costs ought to be evaluated over the asset's or the asset system's life cycle, i.e. from acquisition/creation, utilization, maintenance to ultimate renewal/disposal. As these aspects vary at various stages of the life cycle, elements of performance evaluation and improvement are necessary in the asset management structure and, similarly, in the risk management framework to affirm the relevance and accuracies of their portrayals.

The overview of an asset management system, as depicted by PAS 55:2008, can be found in Fig. 3. Within which, the use of terminologies such as asset systems and criticalities reverberate the key concepts that have been highlighted above.

ISO 31000-Risk management

ISO 31000 (International Organization for Standardization 2009) offers its interpretation of a risk management framework. It dictates that there should be four main stages, namely, establishing the context, risk assessment, risk treatment, and monitoring and review. Before assessing any risks, the context under which the assessment is to be executed should be defined. One important aspect is the risk criteria, which are essential as they are used for evaluation of risk significance. Depending on factors such as the views of stakeholders and the nature of the industry, risk criteria can vary from organization to organization. One way by which risk criteria can be defined is via risk matrices, which will be touched on later in a subsequent subsection.

The risk assessment stage consists of three sub stages, namely risk identification, risk analysis and risk evaluation. The risk identification sub stage generates a comprehensive list of failure modes that are capable of jeopardising the functionality or performance of the asset or asset system. All credible failure modes should be identified here, otherwise it will be left out from the assessment totally. The risk analysis sub stage develops an understanding of the risk associated with each failure mode by determining its likelihood and consequences. Lastly, the risk evaluation sub stage identifies risks which need treatment and the priority by which treatment should be implemented.

Information sources such as historical data, experience, stakeholder feedback, observations, forecasts and expert judgement can be used for risk analysis. However, ISO 31000 explains that, in order for risk management to be effective, it should be based on the best available information which can be facilitated via a feedback loop of monitoring and review. This stage enables the organization to correct risks which have been inaccurately assessed and, in so doing, reduce discrepancies as soon as more accurate data presents itself. This stage coincides well with PAS 55:2008 which mandates the element of performance and condition monitoring in asset management systems.

ISO 15288:2008-System life cycle process

ISO 15288:2008 identifies seven phases in a system life cycle. These are namely the exploratory phase, concept phase, development phase, production phase, utilization phase, support phase and retirement phase. During the exploratory phase, research studies are undertaken to generate new concepts or capabilities which can ultimately lead to the initiation of new projects. In the concept phase, these concepts or capabilities are further specified with guidance from the risk management process which commences from this phase. Stakeholders' needs are identified, clarified and documented as system requirements (International Organization for Standardization 2008). From the system requirements, evaluation on risks and opportunities are then executed to arrive at the appropriate design specifications (International Organization for Standardization 2008).

Subsequently, the system is developed in the development phase while the system components are produced and integrated in the production phase. Verification and validation activities are executed throughout these phases to ensure continued compliance to system requirements (International Council on Systems Engineering 2015). Once the system is commissioned, the utilization and support phases run in parallel. The former ensures operational effectiveness while the latter supports system operation with logistics, maintenance and support services (International Council on Systems Engineering 2015). Finally, the system and its associated services are removed in the retirement phase. In any of these phases, risks can be introduced or altered. During the utilization phase, for instance, the operating environment of the system can change unexpectedly and lead to significant alteration in risk behaviour. Thus, in line with ISO 31000, the iterative process of risk assessment, risk treatment, and monitoring and review should perpetuate throughout the system's life cycle and can only end at the retirement phase.

In Fig. 4, the risk management process as defined by ISO 31000 has been incorporated into the system life cycle as defined by ISO 15288 to illustrate where each stage of the risk management process is applicable in a system life cycle. This systems representation of the risk management framework underlines the message that risk management ought to be a continuous feedback loop which stretches throughout the system life cycle.

EN 50126-Railway applications: Specification and demonstration of RAMS

In Europe, EN 50126 provides railway industry guidance on how reliability, availability, maintainability and safety ("RAMS") can be managed. It elaborates that, in order for safety and availability targets to be achieved, reliability and maintainability requirements need to be met, and maintenance and operational activities need to be controlled. The correlations between the elements of RAMS are portrayed in Fig. 5. In the jurisdiction of risk management, it corroborates with PAS 55:2008 that risk analysis shall be performed at various phases of the system life cycle. The system lifecycle, applicable to the rail context, has been suggested by EN 50126 to be as depicted in Fig. 6. This model follows quite closely with the generic lifecycle model proposed by ISO 15288: Phases 1 to 5 correspond with the exploratory and concept phases, 6 to 10 to the development and production phases, 11 to the utilization and support phases and, lastly, 14 to the retirement phase of the generic lifecycle model. However, this system lifecycle seems to suggest at face value that risk analysis is just a one-time activity when, in fact, EN 50126 acknowledges that risk management ought to be an on-going process that perpetuates throughout the system lifecycle.

EN 50126 also recommends that risk analysis at each stage be performed by the authority responsible for that phase. This may not be judicious as such clear segregation of responsibilities can lead to future risks being overlooked and the loss of opportunities to nip risks in the bud before they manifest. In Europe, heavy fragmentation of rail industry could aggravate the risks. This problem is averted with the guidance from PAS 55:2008 that risk should be evaluated for the entire system life cycle at any point in time.

EN 50126 agrees that three main stages, namely, specification, risk analysis and risk evaluation, should form part of the risk management process. Specifically, the usage of a risk matrix is recommended for risk evaluation. The risk matrix is a risk management tool rationalised across an organization which prescribes the significance of risks. The tool first requires the likelihood and severity of the risk to be categorized based on defined categories. Based on the likelihood category and the severity category which the risk falls into, the risk category, also known as risk criticality, can then be read off from the risk matrix. However, pertaining to the categorization and risk matrix that EN 50126 has proposed, there are two main concerns. Firstly, risks are evaluated based on their frequencies of occurrence. Risk is in fact a function of likelihood and not a function of frequency. The use of frequency categories can lead to risks of failure patterns which are time dependent to be erroneously misrepresented. This can be a significant problem as Fig. 7 shows that, according to the concept of six RCM failure patterns, only one has a fixed rate of failure throughout the asset's life.

Besides this, critical, marginal and insignificant severity has been defined as the loss of major system, severe system damage and minor system damage respectively. This is another area for concern because it is ambiguous on what defines a major system and what warrants severe system damage. To reduce subjectivity in the risk evaluation, this ambiguity can be removed by simply quantifying as far as possible the definition of severity and likelihood categories.

The specification of categories and risk matrix depends on the organization's values, objectives and resources, and should take into consideration any relevant legal and regulatory requirements (International Organization for Standardization 2009). Thus, these will not be specified in the paper. Nevertheless, for the example later, a hypothetical risk matrix will be adapted from EN50126 with the two areas of concern highlighted above addressed.

Integration of reliability tools

Reliability tools presented in Section 2 are incorporated into the model in Fig. 4 to form a preliminary risk assessment framework as shown in Fig. 8. FMEA triggers the practitioner to identify credible failure modes (risk identification), assess the risks for these failure modes (risk analysis), rank the risks in terms of criticality and identify the most appropriate action for each risk (risk evaluation). Accordingly, step 1 in FMECA establishes the context prior to risk analysis. Path 1 to Path 3 development stages are equivalent to the risk identification and risk analysis stages. Step 5 corresponds with the risk evaluation stage. Last of all, Steps 6 and 7 represent the monitoring and review stage.

Note that, if FMECA were to be used independently for risk identification, not all credible failure modes may be captured. This is undesirable as any failure modes left out in the risk identification sub stage will be left out from the analysis altogether. However, when FMECA is complemented with FTA, the modelling approach of the latter is able to ensure that identification of credible failure modes is comprehensive and holistic. In particular, FTA can be deployed on the identification of failure modes and the causes behind each failure mode in Path 1 and Path 2 development steps of FMECA. This is a combination of FMECA and FTA.

In theory, the proposed framework integrates the element of monitoring and assessment for enforcing a proactive inspection and maintenance regime for rail fasteners. This aim would be achieved through the use of risk matrix for risk evaluation which addresses the need for optimizing resource allocation. Apart from that, the embedment of FTA with FMECA within the integrated framework assures that the regime is comprehensive.

Application

An example has been constructed to demonstrate how the risk management framework can be applied in practice. This example shall focus on the imbedded anchor, indicated as the plate screw in Fig. 1.

Stage 1: Establishing the context

Amendments have been made to the risk matrix in EN 50126. Firstly, the correct portrayal of failure behaviours has been promoted by classifying occurrence in terms of probability instead of frequency. Secondly, ambiguity is reduced by providing, wherever possible, numerical values for likelihood and severity categorization. The resultant risk matrix is similar to that suggested in academia (Duan et al. 2016; Dumbrava and Iacob 2013) and implemented in industries (Sutton 2010). The adopted risk criteria will be that risks must be resolved before they migrate into the intolerable risk category.

Stage 2: Risk assessment

Fault Tree Analysis for risk identification

A fault tree analysis was executed to identify the failure modes which are applicable for imbedded anchors. The fault tree diagram, as shown in Fig. 9 will form the basis for the ensuing FMECA.

Risk analysis

i. FMECA

By identifying credible failure modes, the FTA conducted in the previous section sets the stage for FMECA. FMECA then analyses each failure mode individually for the likelihood of its occurrence and the severity of its associated consequence. In the subsequent demonstration, only one of the time-dependent failure modes will be put through FMECA. This failure mode has been chosen to be the reduction in component strength due to corrosion.

Considerations will now be made on whether Monte Carlo simulation is applicable. A Federal Railroad Administration research from 2011 had concluded that a minimum of three consecutive rail fasteners failures is required for gauge widening to be a credible concern (Federal Railroad Administration 2011). In addition, the Asset Standards Authority under Transport for North South Wales recommends that, for curves less than 1000m in radius, failure of three consecutive rail fasteners require a Priority 2 response. Beyond which, an emergency response would be warranted (RailCorp Network 2013). As multiple rail fasteners are required to fail in order for an undesired event to occur, risk should be evaluated from an asset system level, i.e. from a rail fastening system perspective. According to the risk management framework, Monte Carlo simulation should be considered for the example.

In Table 2**,** the failure effect has thus been identified as a potential derailment scenario (The Office of Transport Safety Investigations 2014) which arises when more than three consecutive rail fasteners fail. If this is a track with frequent passenger service, derailment can potentially lead to fatality with severe disruption of train service. As such, this failure effect has been accorded in Table 2 a severity category 1 for both effect on people and financial damage.

ii. Weibull analysis

The relationship between the shape parameter of Weibull distribution and RCM failure behaviour is shown in Fig. 10. Corrosion increases in severity with time, thus Weibull distribution for imbedded anchor corrosion is expected to assume a slope parameter of more than 1. It has been specifically suggested by the Weibull handbook that, for corrosion and erosion related failure modes, the shape parameter can be predicted to be between 2 and 3.5 (Robert B Abernethy 1996). The scale parameter, on the other hand, is defined as the timeframe at which there is a 63.2% chance that the component will fail. This parameter is thus analogous to the average lifespan of the component. The average lifespan of rail fasteners can thus vary substantially and this variability needs to be reflected in the analysis of the framework.

iii. Monte Carlo simulation

The assumptions and corresponding bases made for the Monte Carlo simulations are as follow. These assumptions have also been illustrated in Fig 11.

- System definition: A rail fastening system will be defined by the smallest unit possible, i.e. a rail section which is anchored by five consecutive rail fasteners,
- Assumption: According to Network Rail standards for Inspection and Maintenance of Permanent Way, three consecutive missing or ineffective rail fastenings will warrant the

maximum priority level of M1*, i.e. rectify as soon as practicable (Network Rail, 2009). Thus, the system is said to be failed when more than 3 consecutive rail fasteners fail.

- Assumption: When a sleeper is unable to support a train-induced load, the adjacent sleepers will be required to carry loads which are higher than normal, reducing their remaining lives. The extent to which lives are reduced are as suggested above (Zhao et al. 2007). As rail fasteners are subjected by the same loads which are subjected to the sleepers, parallels will be drawn between the remaining lives of sleepers and that of rail fasteners. Thus, when one rail fastener fails, the residual life of the adjacent fastener reduces by 50%. If a rail fastener is bounded by two failed fasteners, its residual life is reduced by 75%.

Stage 3: Risk evaluation

In Fig. 12, the availability of a single rail fastener has been plotted against that of a rail fastening system for the Weibull distribution of scale parameter 8000 and shape parameter 3. There are two main observations that can be made from Fig. 12. Between 0 to approximately 5670 days, the availability of the rail fastening system is higher than that of a singular rail fastener. However, beyond this timeframe, the availability of the rail fastening system deteriorates faster than that of a singular rail fastener.

The availability of the rail fastening system is linked to the availability of multiple rail fasteners. Thus, even if a rail fastener fails prematurely, the rail fastening system will remain supported by fasteners with longer useful lives and does not fail until three consecutive rail fasteners fail. This explains the first phenomenon.

This dependency, however, often causes the availability of the rail fastening system to be determined by the three shortest useful lives of its constituent fasteners. Besides, the failure of one rail fastener reduces the residual lives of the subsequent fasteners. Thus, the second phenomenon results.

The time required for probability to transit from E to D, to C, to B and then to A can be read from Fig. 13 using the definition of probability categories from Table 3. For the rail fastening system, probability transits to D after 1937 days, to C after 2438 days, to B after 3202 days, and finally to A after 4388 days. In fact, there is no difference in severity categories for effect on people and financial damage; the failure of a rail fastening system amounts to a severity level of I for both. Therefore, for both effect on people and financial damage, risk is tolerable for the first 1937 days, then undesirable for the subsequent 501 days and, beyond which, intolerable. This analysis result has been updated in the Failure Mode, Effect and Criticality Analysis in Table 4. It can also be noted from Fig. 13 that the probability of failure for a singular rail fastener transits to C after 796 days. This means that, if risk is erroneously depicted at the component level instead of the system level, the organisation could have been misguided in taking action at one-third of the actual allowable timeframe, i.e. within 796 days instead of within 2438 days, leading to a less-than-optimal allocation of maintenance resources within the organisation. In the next sub-section, it shall be further demonstrated on how the evaluated risks can be used for the optimization of maintenance resources in risk treatment.

Stage 4: Risk treatment

In the corrective approach, only rail fasteners which have failed are replaced. Currently, rail fasteners are inspected on a fixed frequency and the timeframe for action is determined by the condition of the defect. In this sub-section, risk assessment is used to optimize this approach further by extending the intervention interval until risk migrates into intolerable category. The orange arrows in Fig. 14 shows how the availability of the rail fastening system would evolve under this optimized corrective approach. Each black dot indicates the point in time where intervention is required prior to migration to intolerable risk. Table 6 shows that maximum intervention intervals should be gradually reduced with time to prevent intolerable risk. As the current inspection and maintenance regime looks at the extent of deterioration and not the rate of deterioration, there may come a point in time when risk becomes intolerable if the priority of action is unable to catch up with the risk transition timeframe.

In the proactive approach, all fasteners are inspected and those which have failed or are expected to fail within the next few years are proactively replaced. The replacement includes those that are expected to fail within a specified number of years from the point of intervention. Apart from that, only one point of intervention is considered and the blue lines correspond to various extents of proactiveness at that intervention. The extent of proactiveness is adjusted by varying the projected number of years from that point of intervention. The results can be seen from Table 6 and Fig. 15. In general, proactively changing rail fasteners increases the availability of the rail fastening system more than if done by the optimized corrective approach. As shown in Table 7, if 21% of the worst rail fasteners are changed out proactively, fastening systems reach intolerable risk after 2651 days. Reactively changing 21% of the rail fasteners, on the other hand, averts intolerable risk for 2481 days.

However, from an execution perspective, proactive maintenance would require all imbedded anchors to be removed for inspection and subsequently reinstated post inspection. This is not only time-consuming but also exposes the rail fastening system to additional infant mortality risks. In addition, making a judgement on whether a rail fastener will fail within the next few years can also be very subjective. Thus, while proactive maintenance is ideally a more effective risk mitigation approach, the amount of resources and complexities associated to its execution does not make it a viable strategy.

Another approach would be to renew the imbedded anchors of the rail fastening system, regardless of their condition, and by doing so, eliminate the subjectivity that characterises the pro-active approach. To optimize maintenance resources, renewal can be synchronised with the time at which risk migrates into intolerable risk category, i.e. after 2417 days in service. Upon complete renewal, the risk at question resets fully and will only migrate into intolerable after another 2417 days. This approach appears to be more effective than the optimized corrective approach as the timeframe at which risk migrates to intolerable risk is more than three times longer than that for the latter. This proposition, however, needs to be carefully evaluated against other factors. One such factor is the consideration that, like the proactive approach, this strategy involves all rail fasteners as any segments that remain un-renewed will continue to see risk propagate into the intolerable category. Thus, it may not be as effective as it seems as it requires more resources and introduces more infant mortality risks.

There are a few factors that can define what is the most appropriate approach to adopt. These factors include the amount of additional risks introduced and the cost effectiveness associated with each approach. This sub-section will delve specifically into how cost effectiveness can be evaluated and compared between the optimized corrective approach and the renewal approach. Table 5 states that five corrective cycles are required to prevent migration of risk into the intolerable category for a duration of 4898 days. For the case of the renewal approach, only one cycle is required to achieve the same effect. With effectiveness of risk mitigation approximately equivalent between five corrective cycles and one renewal cycle, the associated costs can be evaluated using Net Present Value analyses to compare the cost effectiveness for these approaches. In the following NPV analysis for the optimized corrective approach, Year 0 is defined as the year in which the first corrective intervention is to be executed. Let the cost of renewing all fasteners at Year 0 be X, the discount factor be 5%, and the effect of inflation to be negated.

In Year 0, 2.73% of the fasteners require replacement, thus the cost for the first corrective cycle is indicated as 0.0273X. Subsequently, 3.37%, 3.48%, 3.59% and 3.73% require replacement in Years 2, 3, 4 and 5 respectively. The total cost for five corrective cycles in terms of net present value becomes approximately 0.15X. It can be concluded that, while one renewal cycle has a greater impact in terms of risk mitigation, the renewal approach is at least six times less cost effective when compared with the optimized corrective approach.

Nevertheless, as the intervention intervals for the optimized correction approach becomes increasingly shortened, there will come a stage where maintenance resources become strained or where the long-term cost of the optimized corrective approach outweighs that of the renewal approach, such that the latter becomes a more viable option. This conclusion has been updated into the Failure Mode, Effect and Criticality Analysis in Table 7.

The example has demonstrated the effective use of FTA in conjunction with FMECA for risk identification. When executed methodically, this combination allows the comprehensive identification of credible failure modes and the systematic risk analysis of each failure mode. This example has also shed light on how risk can be assessed quantitatively and how it can subsequently be used for selecting the optimal risk treatment option. When diverse options are available for risk treatment, a life cycle cost analysis can be done for cost effectiveness comparison.

Discussion

Monte Carlo assumptions could have significant effects on the probability analysis and ultimately the appropriate risk treatment to adopt. These rules, if defined too conservatively, can lead to lost opportunities in maintenance optimization. Conversely, if the failure mode is not well understood or if over-optimistic rules have been set, undesired consequences may materialise before expected. In this regard, the second assumption has thus been modified such that, when a rail fastener fails, the residual life of the fastener which is one position away reduces by 30% while that which is two positions away reduces by 20%. The simulation is then repeated to understand how this ultimately affects the risk analysis. The new set of assumptions is listed below and illustrated in Fig. 16.

- No change in system definition: A rail fastening system will be defined by the smallest unit possible, i.e. a rail section which is anchored by five consecutive rail fasteners
- No change in first assumption: Rail fastening system fails when three consecutive rail fasteners fail
- Amendment in second assumption: When one rail fastener fails, the residual life of the adjacent fastener reduces by 30%. That of the subsequent fastener reduces by 20%.

Table 8 and Fig. 17 illustrate the results from the amended simulation. The blue line indicates the availability curve of a singular rail fastener. The red solid line, on the other hand, indicates the availability curve from the case study simulation and the red dotted line indicates that of the amended simulation. It is observed that the change is mainly characterised by a parallel shift in the availability curve to the right. The change in the risk transitions has been found to be rather pronounced. Specifically, transition to intolerable risk has been shifted back by 8.5%, from Day 2432 to Day 2641.The second aspect is the number of consecutive rail fasteners which constitutes a rail fastening system failure. Based on Network Rail's track inspection standards, the case study has assumed this number to be three. The track inspection standard from Australia, however, advises that immediate corrective action is required if four consecutive rail fasteners have been found to have failed (Asset Standards Authority, 2013). The higher tolerance in the latter means that there is a lower amount of safety margin. The Monte Carlo simulation has been modified in accordance to the latter guidance and repeated to understand how this affects the risk analysis. The new set of assumptions is listed below and illustrated in Fig. 18.

- Change in system definition: A rail fastening system will be defined by the smallest unit possible, i.e. a rail section which is anchored by seven consecutive rail fasteners
- Change in first assumption: Rail fastening system fails when four consecutive rail fasteners fail
- No change in second assumption: When one rail fastener fails, the residual life of the adjacent fastener reduces by 50%. If a rail fastener is bounded by two failed fasteners, its residual life is reduced by 75%.

Using similar line representations as Fig. 17, Fig. 19 illustrates the results from the amended Monte Carlo simulation. The availability curve has similarly shifted to the right. However, its gradient has steepened and the curve intercepts the original availability curve. It is also observed from Table 9 that transition into intolerable risk has been shifted back by a significant 19%, from Day 2437 to Day 2899.

The above analysis underscores the importance of understanding how the failure mode relates to the undesired consequence. Inadequate understanding or having too low a safety margin can spread the butter too thin, causing undesired consequences to transpire. On the other hand, having conservative safety margins can translate to suboptimal resource allocation.

Conclusion

The current inspection and maintenance regime for rail fasteners has been assessed and opportunities have been found in terms of preventing undesired consequences and allocating resources. These opportunities are namely in increasing its comprehensive, proactiveness and resource optimization. As a result, this study proposes capitalizing these by shifting towards risk-based maintenance and puts forth a risk management framework to facilitate and reinforce this. A novel framework for integrated risk-based maintenance planning has been developed in this study. The structure of the risk management framework is mainly extracted from ISO 31000 which advises that the main stages should include establishing the context, risk identification, risk analysis, risk evaluation, risk treatment and, lastly, monitoring and review. PAS 55:2008 recommends that asset management activities ought to be executed across the asset life cycle. To inculcate this philosophy, a system lifecycle has been integrated into the framework to provide a systems perspective. For risk evaluation, EN 50126 advises that the appropriate reliability tool to use is the risk matrix. For other risk assessment stages, appropriate reliability tools have been studied and the circumstances under which each are applicable have been understood.

An example is then prepared on the imbedded anchors on rail fasteners. Its intention is to highlight how the risk management framework can be innovatively adopted in practice and how it delivers on the improvement opportunities. In the example, the timeframes at which risk for corroded imbedded anchors transits to different risk categories were obtained. The overall outcome of this exercise can be found in Table 7. The example has been demonstrated on how FTA can be used for the systematic identification of credible failure modes and how FMECA ensures that risk is evaluated for each failure mode identified. Life cycle analysis is then conducted to demonstrate how the optimal risk treatment strategy can be sought for resource optimization. The Weibull analysis used is inherently a monitoring and review reliability tool. It should be noted that findings are unique to the example and should be treated carefully. Thus, before the novel framework can be applied onto other failure modes, it is imperative that the framework is simulated and analysed for the identification of any unique considerations that may affect the framework's effectiveness.

Acknowledgement

All authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network,” which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing.

Reference

Ahn, J., and Chang, D. (2016). “Fuzzy-based HAZOP study for process industry.” *Journal of Hazardous Materials*, 317, 303–311.

Arunraj, N. S., Mandal, S., and Maiti, J. (2013). “Modeling uncertainty in risk assessment: An integrated approach with fuzzy set theory and Monte Carlo simulation.” *Accident Analysis & Prevention*, 55, 242–255.

Authority, A. S. (2013). Guide to Transport for NSW Framework for Assuring the Safety of Rail Assets and Infrastructure. New South Australia.

Barlo, T. ., and Zdunek, A. . (1995). *Stray current corrosion in electrified rail systems - Final report*.

Duan, Y., Zhao, J., Chen, J., and Bai, G. (2016). “A risk matrix analysis method based on potential risk influence: A case study on cryogenic liquid hydrogen filling system." *Process Safety and Environmental Protection*, 102, 277–287.

Dumbrava, V., and Iacob, V.-S. (2013). "Using probability - Impact matrix in analysis and risk assessment projects." *Journal of Knowledge Management, Economics and information Technology*, 76–96.

Federal Railroad Administration. (2011). "Effect of missing or broken fasteners on gage restraint of concrete ties." U.S. Department of Transportation,.

International Council on Systems Engineering. (2015). *Systems Engineering Handbook - A Guide For System Life Cycle Processes and Activities (Fourth ed.)*. John Wiley & Sons, San Diego.

International Organization for Standardization. (2008). "ISO/IEC 15288:2008 Systems and software engineering -- System life cycle processes." ISO/IEC-IEEE, United States of America.

International Organization for Standardization. (2009). *BS ISO 31000:2009 Risk management - Principles and guidelines*. BSI.

Kernes, R. G., Shurpali, A. A., Edwards, J. R., Dersch, M. S., Lange, D. A., and Barkan, C. P. L. (2014). "Investigation of the mechanics of rail seat deterioration and methods to improve the abrasion resistance of concrete sleeper rail seats." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(6), 581–589.

Network Rail. (2009). "NR/LZ/TRK/00l/A01 Inspection and maintenance of permanent way - Inspection." *Network Rail*, Network Rail, London.

Network Rail. (2017). "NR/L3/MTC/MG0176/11, Prioritisations, reprioritisations and cancellations."

Quality—One International. (2017). *Failure Mode and Effects Analysis (FMEA)*.

RailCorp Network. (2013). "TMC 203: Track inspection." *Engineering Manual: Track*.

RailCorp Network. (2016). *MN A 00100: Civil and track technical maintenance (extracted from formerly ESC 100)*. *Engineering Manual: Common*, Sydney Trains.

Robert B Abernethy. (1996). *The New Weibuil Handbook*. *2nd Revised ed*, Elsevier Science 8: Technology, Oxford, United Kingdom.

Shi, L., Shuai, J., and Xu, K. (2014). "Fuzzy fault tree assessment based on improved AHP for fire and explosion accidents for steel oil storage tanks." *Journal of Hazardous Materials*, 278, 529–538.

Sutton, I. (2010). *Process risk and reliability management*. Elsevier Inc., Burlington, USA.

The Institute of Asset Management. (2008). *PAS 55—12008 Asset management*. BSI.

The Office of Transport Safety Investigations. (2014). *Rail safety investigation report — Main line rail defect, Boronia No. 3 Tunnel*. *Sydney*.

Zhao, J., Chan, A., and Burrow, M. (2007). "Reliability analysis and maintenance decision for railway sleepers using track condition information." *Journal of the Operational Research Society*, 58(8), 1047–1055.

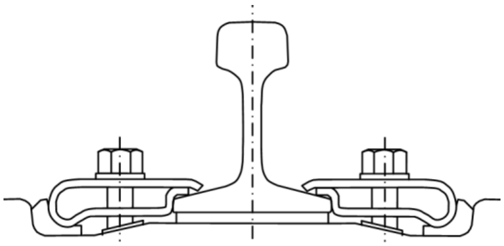

Fig.1. Schematic of anchor bolts on concrete sleeper

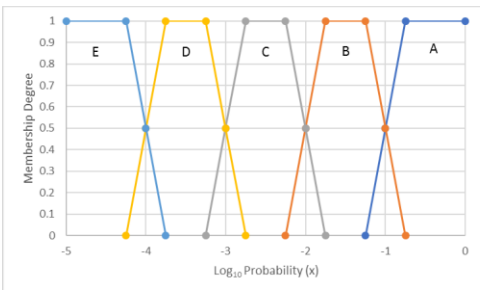

Fig. 2. Trapezoidal membership functions

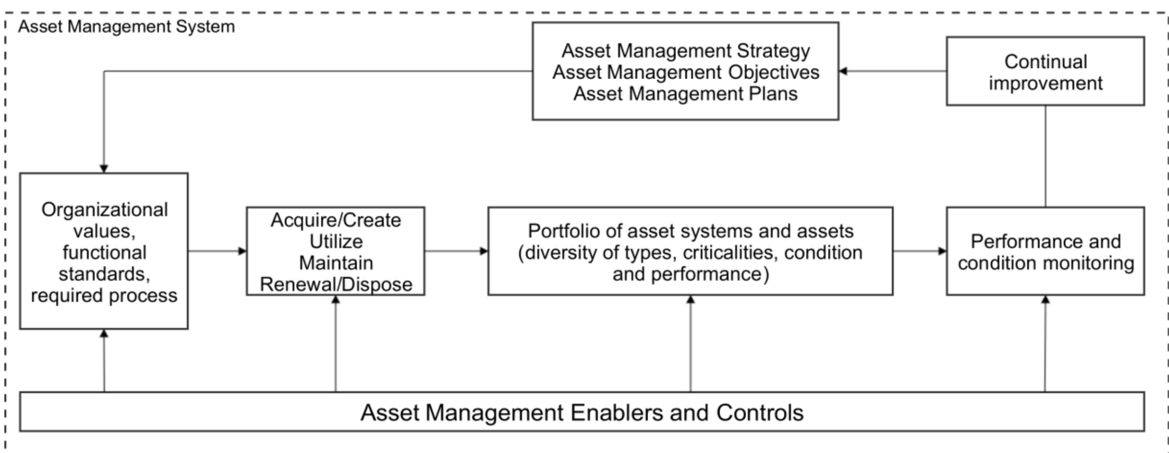

Fig. 3. Overview of asset management system

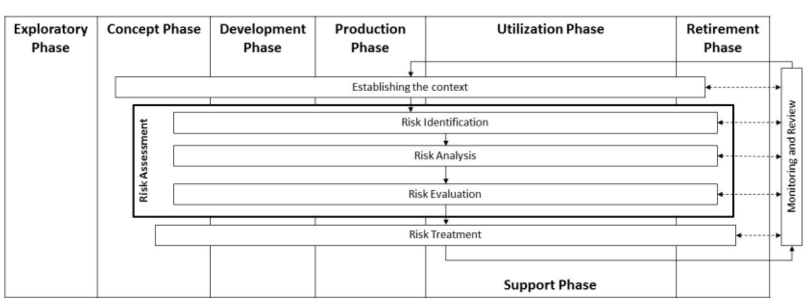

Fig. 4. Systems perspective of risk management framework

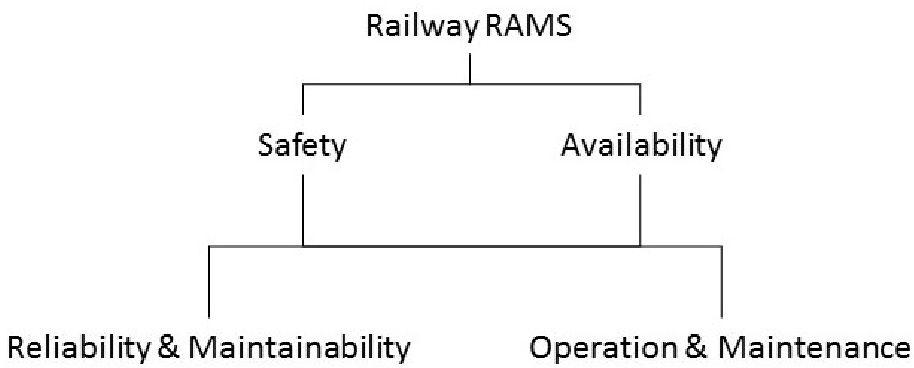

Fig. 5. Relationships between RAMS elements

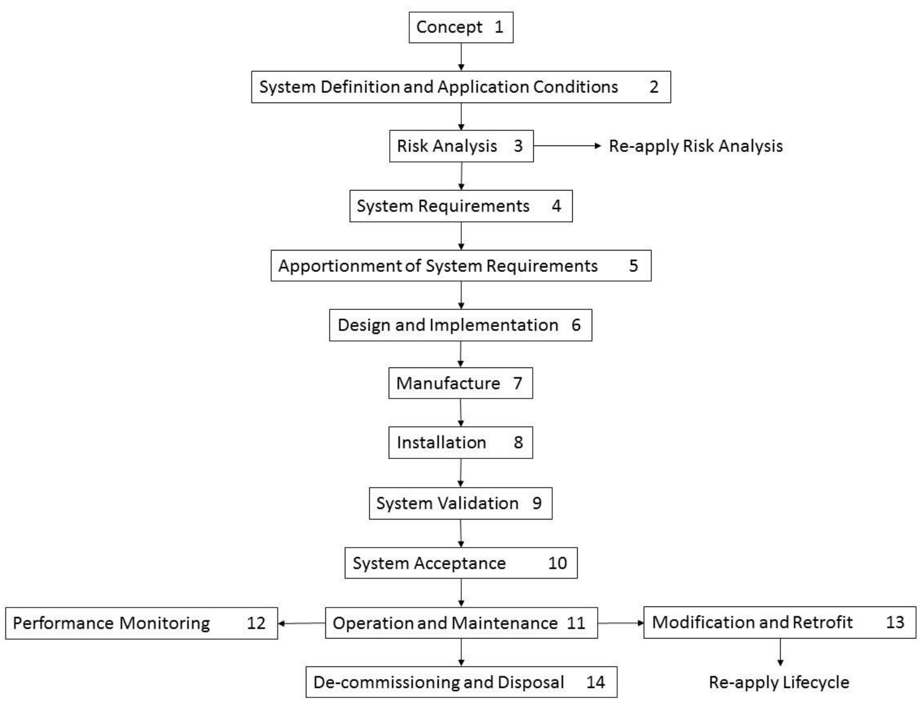

Fig. 6. System lifecycle model

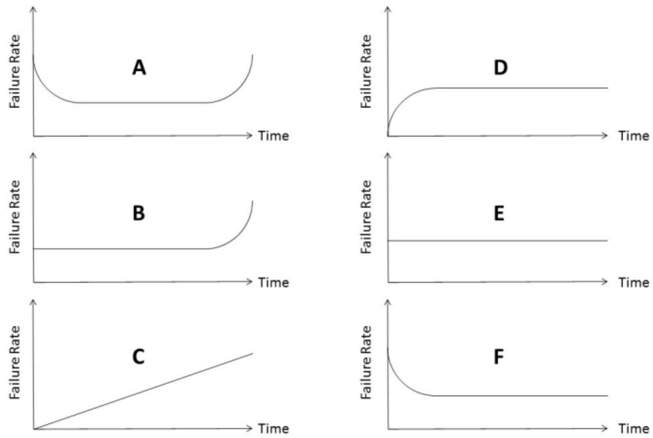

Fig. 7. Six RCM failure pattern curves

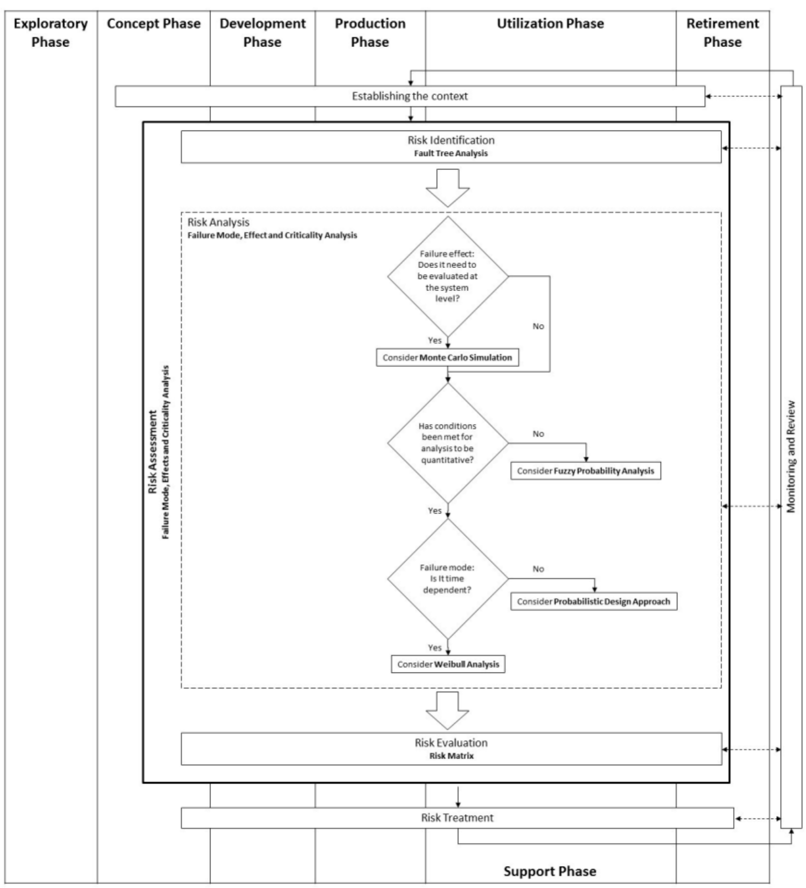

Fig. 8. Preliminary risk management framework

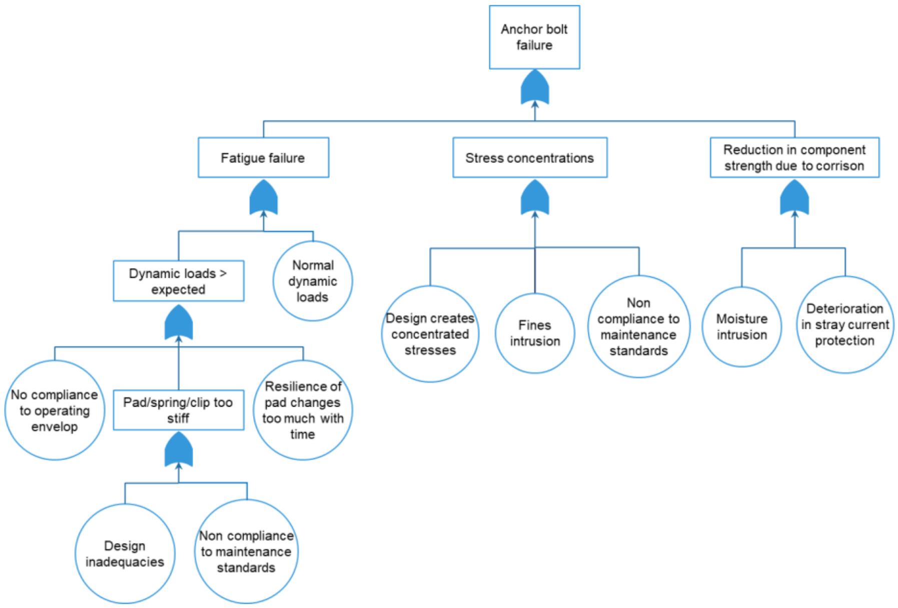

Fig. 9. Fault Tree Analysis for anchor bolt failure

β	RCM failure behaviour curves
< 1	Curve F, part Curve A
= 1	Curve E, part Curve A, part Curve B and part Curve D
= 1.5	
= 2	Curve C
> 2	Part Curve A and part Curve B
= 3.44	

Fig. 10. Relationship between shape parameter and failure behaviour curves

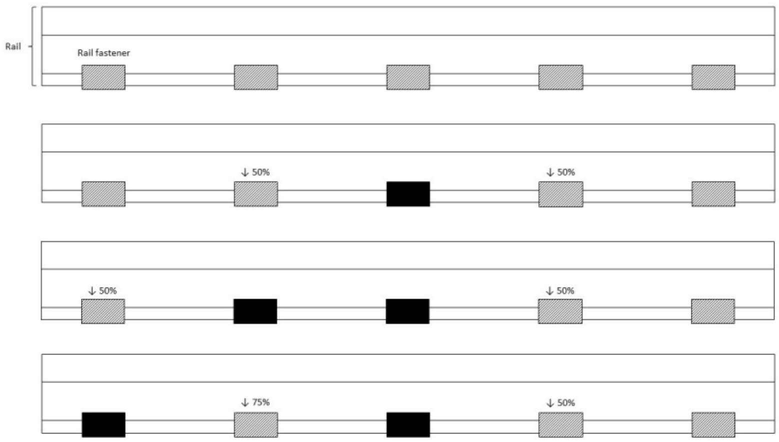

Fig 11. Illustration of the Monte Carlo simulation assumptions

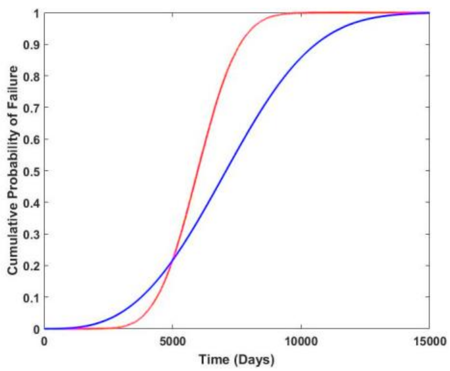

Fig. 12. Cumulative distribution function plot of a single rail fastener (blue) and rail fastening system (red)

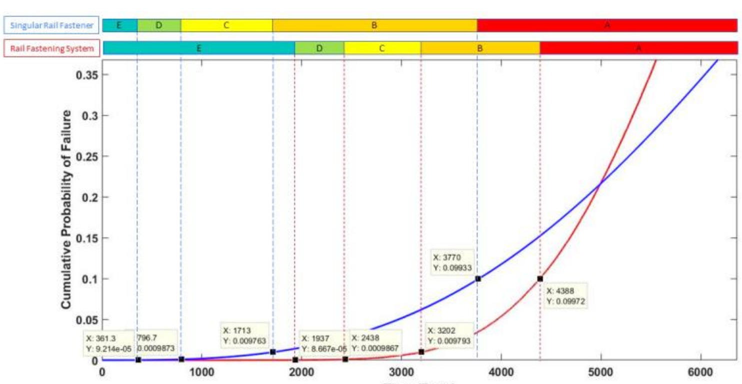

Fig. 13. Timeframe at which probability transits from E to D, to C, to B, to A indicated on the respective cumulative distribution function plots

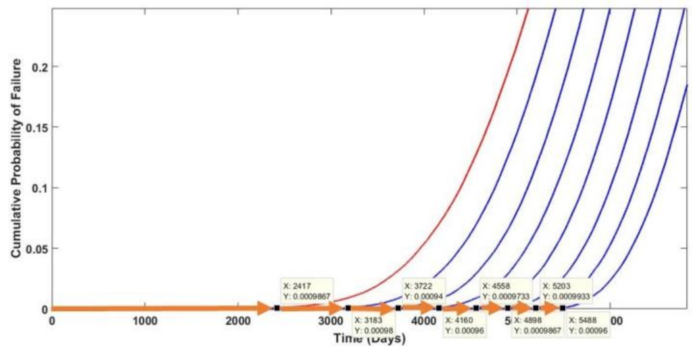

Fig. 14. Availability of rail fastening system after consecutive corrective cycles

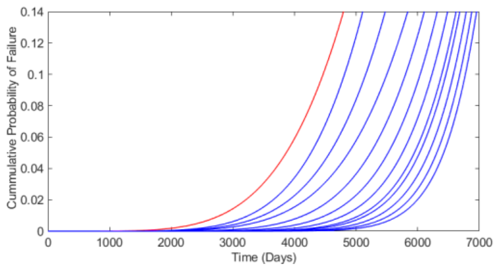

Fig. 15. Availability of rail fastening system with corrective maintenance (red line) and increasing extent of proactive maintenance (blue lines)

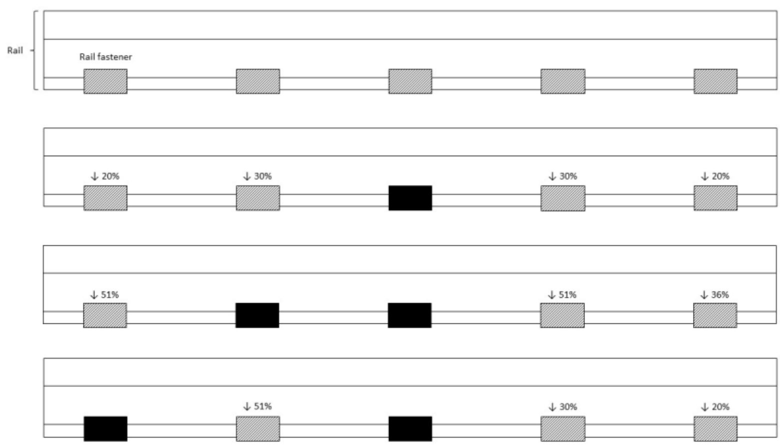

Fig. 16. Illustration of new assumptions, with the impact on adjacent fasteners changed

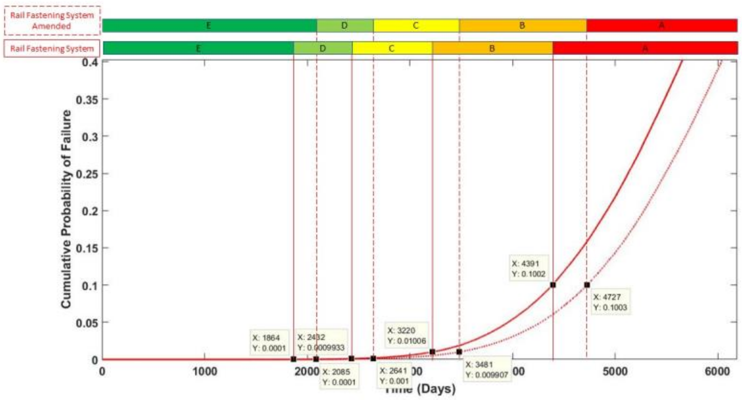

Fig. 17. Shift in availability curve after changes to impact on residual life

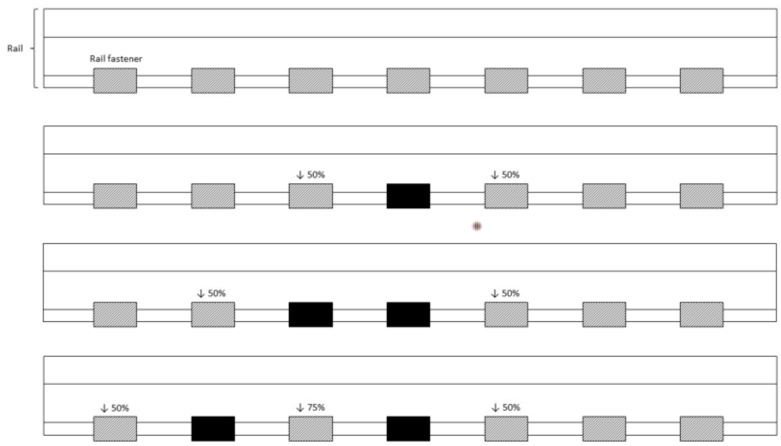

Fig. 18. Illustration of new assumptions, with definition of system failure changed

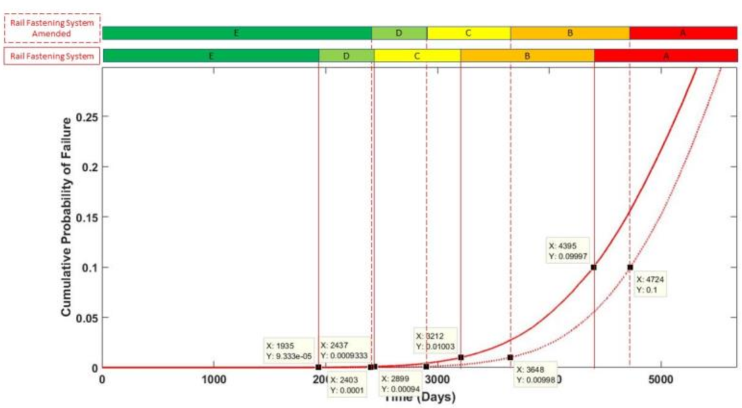

Fig. 19. Change in shape of availability curve after changes on system failure definition

Table 1 Minimum inspection frequency recommended in NR/L2/TRK/001/A01

Inspection frequency	Once per week	Once per two weeks	Once per four weeks
Track category	Cat 1A, Cat 1 & Cat 2	Cat 3 & Cat 4	Cat 5 & Cat 6

Table 2 Failure Mode, Effect and Criticality Analysis after severity assignment

Function	Failure and Cause of Failure	Failure effect	Severity
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: **Severity I** Financial Damage: **Severity I**

Table 3 Risk matrix to be adopted for the example

Likelihood Severity	0.1-1	0.01-0.1	0.001-0.01	0.0001-0.001	0.00001-0.0001
I	Intolerable	Intolerable	Intolerable	Undesirable	Tolerable
II	Intolerable	Intolerable	Undesirable	Tolerable	Negligible
III	Undesirable	Undesirable	Tolerable	Negligible	Negligible
IV	Tolerable	Negligible	Negligible	Negligible	Negligible

Table 4 Failure Mode, Effect and Criticality Analysis after risk assignment

Function	Failure and Cause of Failure	Failure effect	Severity	Probability	Risk criticality
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: **Severity I** Financial Damage: **Severity I**	0 to 1937^{th} day: Probability E 1937^{th} to 2438^{th} day: Probability D 2438^{th} to 3202^{nd} day: Probability C 3202^{nd} to 4388^{th} day: Probability B 4388^{th} day and beyond: Probability A	0 to 1937^{th} day: Tolerable (E-I) 1937^{th} to 2438^{th} day: Undesirable (D-I) 2438^{th} day and beyond: Intolerable (C-I and beyond) Financial Damage 0 to 1937^{th} day: Tolerable (E-I) 1937^{th} to 2438^{th} day: Undesirable (D-I) 2438^{th} day and beyond: Intolerable (C-I and beyond)

Table 5 Change in optimized intervention interval with time

Corrective Cycle	Time of intervention (days)	Elapsed time from previous corrective action (days)	Cumulative percentage of fasteners replaced
1	2417	2417	3%
2	3183	766	6%
3	3722	539	10%
4	4160	438	13%
5	4558	398	17%
6	4898	340	21%
7	5203	305	24%
8	5488	285	n/a

Table 6 Impact of risk mitigation with changing extent of proactive maintenance

Fastener replacement criteria (number of years before failure)	Estimated percentage of fasteners to be changed (%)	Time at which risk next transits into intolerable risk category (Days)
0	3	3180
1	4	3410
2	6	3693
3	8	3978
4	11	4272
5	14	4564
6	17	4818
7	21	5068
8	26	5196
9	30	5231
10	35	5330
11	40	5343
12	46	5352

Table 7 Failure Mode, Effect and Criticality Analysis after risk evaluation

Function	Failure and Cause of Failure	Failure effect	Severity	Probability	Risk criticality	Recommended action
Imbedded anchor - To maintain vertical, lateral and longitudinal position of rail relative to sleepers	Strength reduction due to corrosion	Derailment due to failure of more than three consecutive rail fasteners	Effect on People: **Severity I** Financial Damage: **Severity I**	0 to 1937^{th} day: Probability E 1937^{th} to 2438^{th} day: Probability D 2438^{th} to 3202^{nd} day: Probability C 3202^{nd} to 4388^{th} day: Probability B 4388^{th} day and beyond: Probability A	0 to 1937^{th} day: Tolerable (E-I) 1937^{th} to 2438^{th} day: Undesirable (D-I) 2438^{th} day and beyond: Intolerable (C-I and beyond) Financial Damage 0 to 1937^{th} day: Tolerable (E-I) 1937^{th} to 2438^{th} day: Undesirable (D-I) 2438^{th} day and beyond: Intolerable (C-I and beyond)	Optimized Corrective approach Renewal approach can be expected in future – to be reviewed.

Table 8 Change in probability timeframe after changes to impact on residual life

	Time (days) taken to migrate to			
	Probability D	Probability C	Probability B	Probability A
Case Study	1864	2432	3220	4391
Amended Assumptions	2085 (+221)	2641 (+209)	3481 (+261)	4727 (+336)

Table 9 Change in probability timeframe after changes to impact on residual life

	Time (days) taken to migrate to			
	Probability D	Probability C	Probability B	Probability A
Case Study	1864	2432	3220	4391
Amended Assumptions	2085 (+221)	2641 (+209)	3481 (+261)	4727 (+336)