A risk-based model for inspection and maintenance of railway rolling stock

F. Dinmohammadi, B. Alkali
Department of Mechanical Engineering, School of Engineering and Built Environment, Glasgow Caledonian University, United Kingdom

M. Shafiee
Cranfield University, College Road, Bedfordshire MK43 0AL, United Kingdom

ABSTRACT: Along with the widespread use of high-speed vehicles and the increasing level of traffic on railroads, maintenance management of rolling stock assets is considered to be an area of high priority. In the past, the planning of inspection and maintenance activities for rolling stocks has been based on the accumulated knowledge and experience of train operating companies, rolling stock owners, original equipment manufacturers and vehicle refurbishment companies. However, current research efforts are focused on the development of risk-based maintenance approaches with the major goal of reducing whole life costs while ensuring a high level of transport safety and service quality. This paper presents a novel risk-based modelling approach for the inspection and maintenance management of railway rolling stock assets. A quantitative model is developed to evaluate the time-variant risks associated with different types of failures of rolling stock components. To this aim, the root causes of failures are investigated and a probabilistic method is proposed to estimate the likelihood of occurrence of a failure. The failure consequences taken into account include the costs of inspection, maintenance and repair, the penalty charges due to train delays or service interruption, and the costs of loss of reputation in relation to train cancellations. For the purpose of clearly illustrating the proposed analysis approach, a case study of the Class 380 train's pantograph system operating in a Scottish company is provided and the results are discussed. The model presented in this paper not only provides the capability to assess the current maintenance practices within the railway transport industry but also helps the maintenance engineers to propose or initiate improvement actions when needed.

1 INTRODUCTION

Railway engineering is currently confronted with various problems caused by premature failures of railway assets that require costly and time-consuming maintenance work. The railway assets in general are categorized into two types. The first one is the rolling stock which includes assets that can move on railroad such as locomotives, passenger coaches and freight cars. The other one is the infrastructure which consists of fixed assets such as tunnels, bridges, permanent way, tracks, stations, signaling equipment, etc. Figure 1 illustrates the major components of a typical rolling stock and a rail track structure as two critical assets of the railway industry.

Regular inspection and maintenance of both the passenger/freight trains and the railway infrastructure is essential to ensure network availability and reliability, passenger safety and comfort, and operations efficiency. To this aim, the decision-maker(s) must determine a planning period and find the most appropriate type, frequency and degree (quality) of maintenance actions for all kinds of railway assets such that the total cost incurred over the life span is minimized and/or the reliability of the rail network is maximized.

The rolling stock assets often undergo preventive maintenance (PM) at regular time/mileage intervals which are usually determined based on the knowledge and experience of train operating companies, rolling stock owners, original equipment manufacturers and vehicle refurbishment companies. The rolling stock maintenance tasks typically include inspecting, testing, lubricating and cleaning of vehicles' critical components. The maintenance of the railway infrastructure assets is also preventive in nature and includes repair or renewal of some certain items at pre-determined time intervals or tonnage levels in million gross tons (MGT) (Shafiee *et al.*, 2016).

Despite the best efforts of the maintenance engineers, it is reported in several case studies and publications that a significant portion of railway maintenance resources (e.g. budget, time, manpower) are wasted due to insufficiency or inefficiency of current periodic maintenance and renewal interventions (Scarf *et al.*,2012). One effective way to reduce railway maintenance costs whilst maintaining

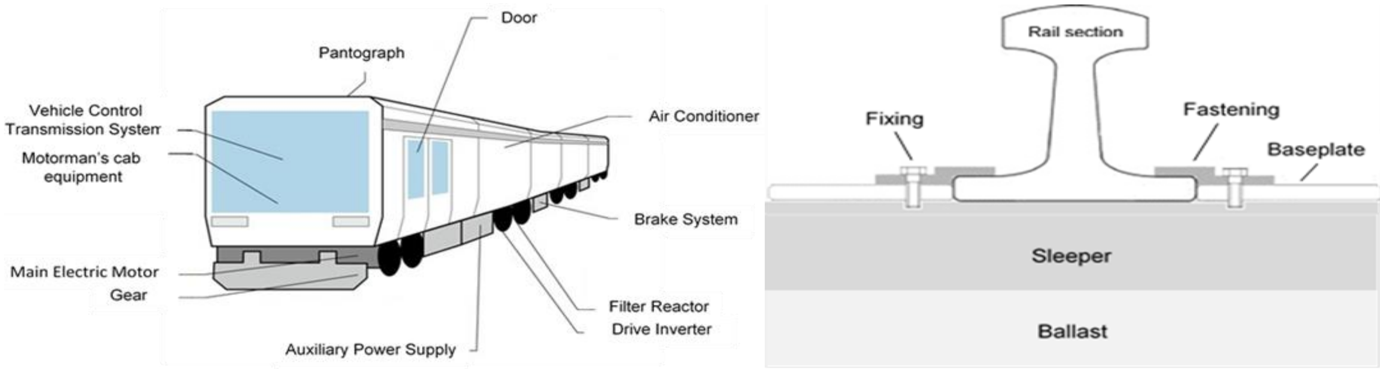

Figure 1. Rolling stock components (left) and the rail track components (right).

a high level of system's reliability and service quality is to develop and implement risk-based methods and tools for inspection and maintenance of assets throughout their entire lifetime. The risk-based inspection and maintenance management of railway infrastructure has received a reasonable attention to date. Below are listed some relevant studies and their findings:

- Carretero *et al.* (2003) presented a reliability centered maintenance (RCM) methodology for large-scale railway infrastructure networks. They also developed a toolkit to show how the RCM analysis can be performed in practice.
- Pedregal *et al.* (2004) applied a predictive maintenance system called RCM^2 to railway turnouts (switches) by integrating two common types of maintenance techniques, namely, reliability centered maintenance and remote condition monitoring.
- Podofillini *et al.* (2006) developed a model to calculate the risks and costs associated with inspection of railway tracks. Then, the authors presented a multi-objective model to optimize the inspection and maintenance procedures with respect to both economic and safety objectives.
- Zio *et al.* (2007) proposed a risk-based approach for improving the service level of railway infrastructure networks. Their approach uses components' importance measures to identify sections of the network having the greatest impact on total delays and passenger disruption.
- Kumar *et al.* (2010) developed an approach for risk assessment of rail defects to support the decision-making process in scheduling of rail inspection and grinding activities.
- Macchi *et al.* (2012) presented a two-stage methodology for the maintenance management of railway infrastructures. The first step of this methodology consists of a family-based approach for equipment reliability analysis and the second step builds a reliability model to identify the most critical items in a railway system.
- Bouillaut *et al.* (2012) presented a Bayesian Networks (BN) approach to model the stochastic degradation process of metro rails and schedule the maintenance activities.
- Le and Andrews (2013) presented a Markov modelling approach to predict the condition of railway bridge elements and then used the model to evaluate the performance of different maintenance strategies.
- Andrews *et al.* (2014) presented a Petri-net modelling approach to predict the state of the rail track geometry under different asset management strategies. The model was then used to estimate the expected whole life costs and schedule the inspection, maintenance and renewal activities.
- Bergquist and Söderholm (2015) proposed a statistical approach using condition data to optimize the condition-based maintenance actions of railway infrastructures.

In spite of the vast literature concerning railway infrastructure maintenance, a survey of the literature shows that there are few studies investigating the application of risk-based techniques and tools to inspection and maintenance of railway rolling stock components. This paper presents a modelling methodology aimed at planning the repair and maintenance tasks of rolling stock components based on risk measures. To this aim, a quantitative model is developed to evaluate the time-variant risks associated with different types of failures in rolling stock assets. The root causes of failures are identified and stochastic methods are proposed to estimate the likelihood of occurrence of a failure. The consequences of failures are modelled using a discounted cost criterion that involves costs of inspection, maintenance and repair, the penalty charges due to train delays or service interruption, and the costs of loss of reputation in relation with train cancellations. The proposed method is applied to a rolling stock pantograph system in a Scottish train operating company and its efficiency is compared to currently used methodologies of maintenance.

The remainder of this paper is organized as follows. Section 2 presents a brief overview of the risk-based inspection and maintenance tools. Section 3 presents a risk-based modelling methodology for inspection and maintenance of rolling stock assets. In Section 4, an application of the model is presented and the results are discussed. Finally, the paper is concluded in Section 5.

2 RISK-BASED INSPECTION AND MAINTENANCE TOOLS

Nowadays, various inspection and maintenance strategies including the periodic, reliability centered, condition-based and predictive maintenance are used in the rail transport industry (Shafiee, 2015). Recently, the application of risk analysis approaches to inspection and maintenance of railway assets is increasing in popularity. As stated in ISO 31000 (2009), risk is defined as "the effect of uncertainty on objectives" and an effect is "a positive or negative deviation from what is expected". In general, risk is a combination of two factors: (1) the probability of occurrence of a failure and (2) the magnitude of the consequences of the failure.

Risk analysis is defined as a systematic use of available information to characterize the likelihood that a specific event may occur and the impact of its likely consequences. The purpose of risk analysis is to determine the overall priority of a hazard so that preventive actions can be taken to reduce and mitigate the most critical ones where resources are limited.

Risk-based inspection and maintenance (RBI&M) is the process of developing an inspection plan based on risk analysis information of failure of assets. In this approach, the assets according to their risk levels are categorized into three groups of high, medium, and low-risk (see Figure 2). High risk assets are the assets with a high likelihood of failure (e.g. soon to fail, old, poor condition) and high consequences of failure (e.g. safety concerns, production losses, environmental impact). On the contrary, low risk assets are the assets whose probability of failure and severity of consequence are low. The remaining assets are considered to have a moderate risk of failure. For high and medium risk assets, a focused maintenance effort is required, whereas in areas of low risk the effort is minimized (Arunraj and Maiti, 2007). So, the maintenance works on different assets are prioritized using risk analysis methods and the required resources are released on a criticality basis.

The main steps of risk-based inspection and maintenance planning are illustrated in Figure 3. In this anlysis approach, the potential failure modes that may threaten the system's performance are identified through data collection, and their associated risks are

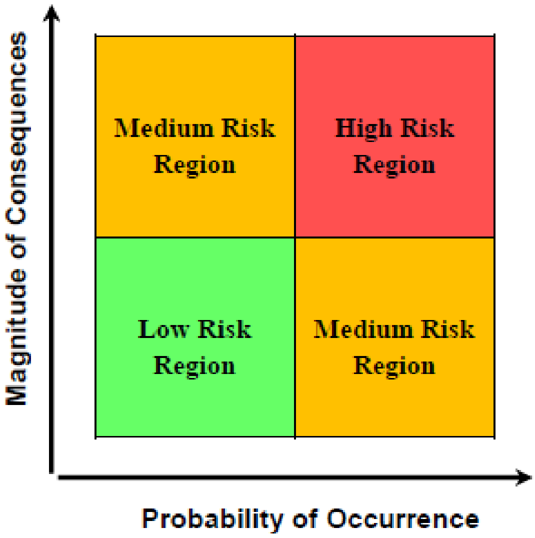

Figure 2. Three regions of risk: high, medium and low.

evaluated by integrating the likelihood of occurrence and the scale of impact. Risk assessments can be either qualitative, quantitative, or a combination of both. The qualitative risk evaluation methods use the judgement and opinions of knowledgeable experts to categorize the risks, while quantitative tools are based on probabilistic and/or statistical models that calculate risk over time. Typically, quantitative risk assessment techniques are more robust than qualitative ones. However, the data requirements for quantitative risk assessment techniques are higher which makes them difficult to apply.

For the risk assessment of systems' failure modes, several tools can be used, e.g. root cause analysis (RCA), fault tree analysis (FTA), event tree analysis (ETA), reliability block diagram (RBD), minimal cut sets, failure mode and effects analysis (FMEA), failure mode, effects and criticality analysis (FMECA), Weibull analysis, design for reliability (DFR), physics of failure (PoF) method, Bayesian reliability, human reliability assessment (HRA), first-order reliability method (FORM), second-order reliability method (SORM). Readers can refer to Andrews and Moss (2002) as a good source of references for RBI&M tools and techniques.

In what follows, we propose a risk-based modelling methodology for inspection and maintenance of rolling stock assets.

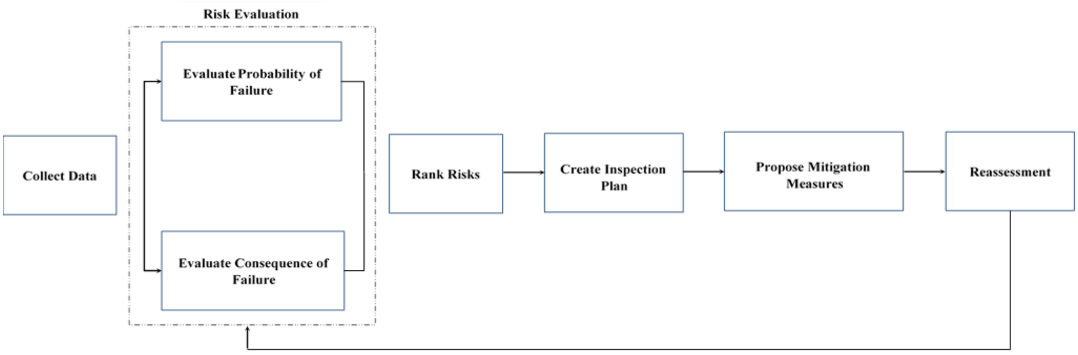

Figure 3. Main steps of risk-based inspection and maintenance planning.

3 MODELLING METHODOLOGY

The proposed methodology for risk-based inspection and maintenance of railway rolling stocks is shown in Figure 4. The nine steps of the methodology are described as following:

Step 1. Consider a rolling stock component for the study.
A railway rolling stock is usually composed of two main parts, namely the car body and the bogie part, each consisting of several components and each performing certain essential functions. Some key components of a rolling stock system include: wheel, door unit, scroll compressor, bogie, pantograph, coupler, brake system, heating and air conditioner, etc. According to the decision makers' criteria, one component is chosen for detailed analysis.

Step 2. Collect the component function information.
Obtaining a good understanding of the component's function and the way in which it interacts with other components is a key task in risk analysis studies. The required information can be collected by answering some of the below questions:

- What functions does the component perform?
- Can rolling stock operate without this component?
- Does the component contain redundancies or backups?
- Will rolling stock fail if the component fails?
- In which ways will the component affect the other components or the overall system?

Step 3. Define all potential failure modes that can cause damage to the component or the rolling stock.
For each component identified, there are one or more failure modes that can occur and negatively impact the system's performance. As each of the components' functions are different, the mechanism of the occurrence of failure may be different from one component to another. The major failure modes in various rolling stock components were identified by expert opinion and are listed as below:

"disconnection, fracture, fatigue, cracked, degraded, deformed, stripped, worn, corroded, binding, leaking, buckled, sag, loose, misalignment, obstruct".

Any of these failure modes or their combination can cause rolling stock to fail. For some rolling stock components, more than one of the above-mentioned failure modes may be present.

Step 4. Identify all root causes that contribute to failure of the rolling stock component.
The identification of primary sources or root causes of failure is an important part of the risk-based approaches. The failures' root causes can be determined by reviewing past failures and using some analytical techniques like RCA or FTA. RCA is a useful process that helps analysts identify and understand the initiating causes of a failure. FTA is a systematic and deductive method which defines an undesired event and then traces all possible reasons that lead to it.

Table 1 presents the common root causes of the failure modes for rolling stock components in six different categories, namely electrical faults, structural damages, functional failures, degradation, errors, and natural (external) hazards.

Table 1. Failure root causes for rolling stock components.

Category	Examples
Electrical	Connection fault, electrical overload, insulation failure, software failure
Structural	Construction and material defects, installation defects, mechanical overload
Functional	Hardware failure, software failure
Degradation	Fatigue, wear, corrosion, ageing, insufficient lubrication
Errors	Human error, calibration error, maintenance error
Natural (external)	Flooding, icing, lightning strike, environmental shocks

It is worth mentioning that more than one failure cause (known as competing risks) may be found for some failure modes of the rolling stock.

Step 5. Determine the total probability of failure from all kinds of causes.
Estimating the probability of failure is a challenging task as it requires a thorough analysis of historical condition data, inspection records, and other factors influencing the performance of rolling stocks. The probability of failure is related to the probability of occurrence of each root cause and can be calculated as follows:

a. Electrical faults

Denote by $POF_1(t)$ the probability that a rolling stock component fails within the time interval (0, t) due to an electrical fault. Then,

$$POF_1(t) = \Pr[\mathrm{T}_{elec} < t] = \mathrm{F}_{\mathrm{T}_{elec}}(t)\,, \tag{1}$$

where T_{elec} represents the time to occurrence of an electrical fault in the component with the corresponding cumulative distribution function (CDF) given by $\mathrm{F}_{\mathrm{T}_{elec}}(.)$.

b. Structural damages

For determining the probability of failure caused by structural damages, a limit states method (LSM) is used. Denote by $POF_2(t)$ the probability that a rolling stock component fails within the time interval (0, t) due to a structural damage. Therefore,

$$POF_2(t) = \Pr[R(t) < S] = F_{R(t)}(S)\,, \tag{2}$$

where R represents the component's load-carrying capacity (often referred to as resistance) whose CDF is given by $F_R(.)$, and S is the load effect resulting from various operating conditions.

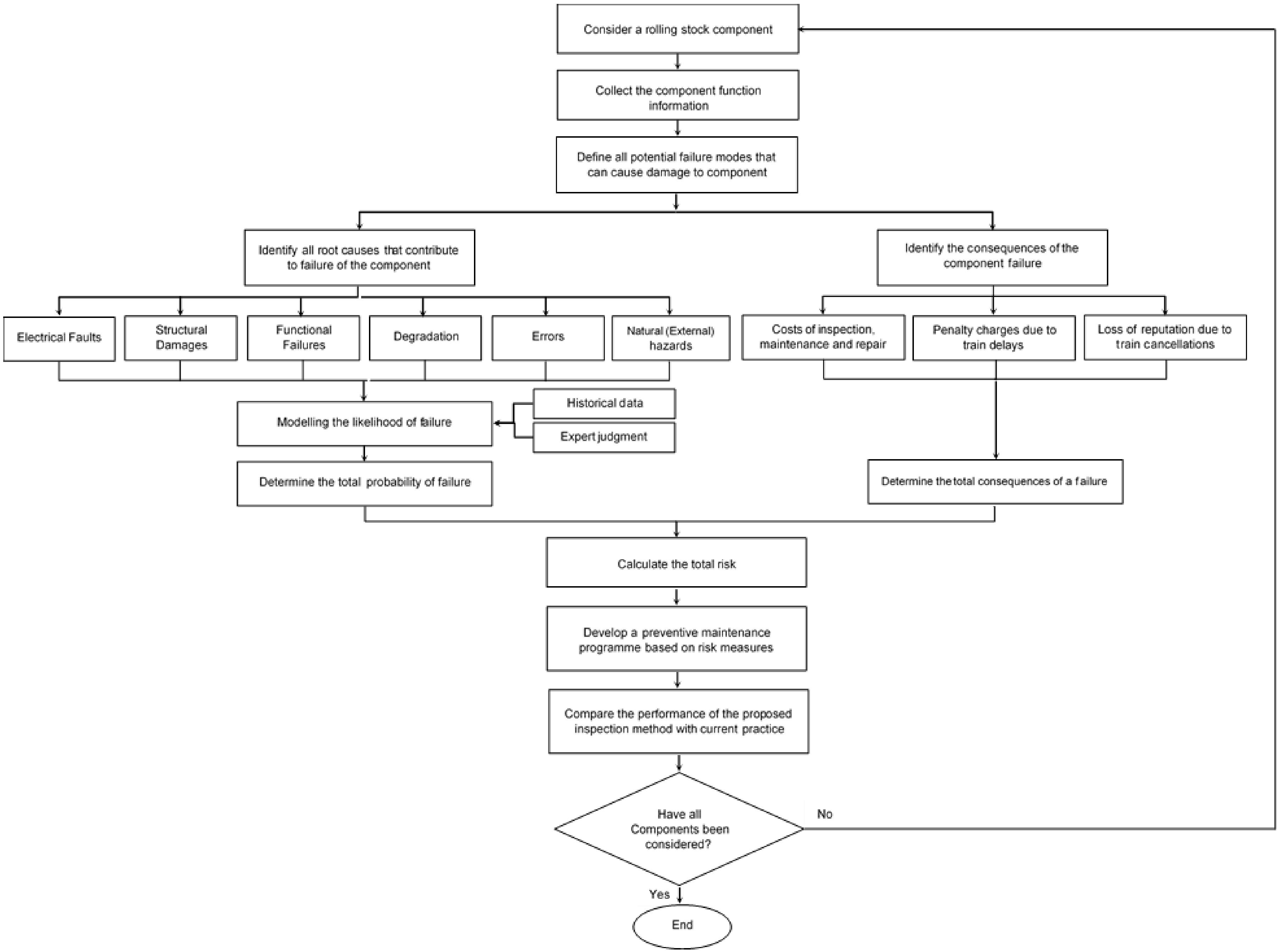

Figure 4. A risk-based modelling methodology for inspection and maintenance of rolling stock assets.

c. Functional failures

Denote by $POF_3(t)$ the probability that a rolling stock component fails within the time interval (0, t) due to a functional failure. Then,

$$POF_3(t) = \Pr[\mathrm{T}_{func} < t] = \mathrm{F}_{\mathrm{T}_{func}}(t), \quad (3)$$

where T_{func} represents the time to occurrence of a functional failure in the component with the corresponding CDF given by $\mathrm{F}_{\mathrm{T}_{func}}(.)$.

d. Degradation

For determining the probability of a degradation failure, a probabilistic cumulative damage model is used in which a failure occurs when the degradation process exceeds a certain threshold level. Denote by $POF_4(t)$ the probability that a rolling stock component fails due to degradation damage. Then,

$$POF_4(t) = \Pr[a_{cr} - A(t) < 0], \quad (4)$$

where $A(t)$ and a_{cr} represent, respectively, the length of a degradation process (e.g. fatigue crack) at time t and the critical length of degradation at which a fracture occurs.

e. Errors

Two different kinds of errors are taken into consideration: the operational error and the human error (Shafiee and Ayudiani, 2015). Let $POF_5(t)$ denote the probability that an error or class of errors will result in a component failure within the time interval (0, t). Therefore,

$$POF_5(t) = \Pr[\mathrm{T}_{err} < t] = \mathrm{F}_{\mathrm{T}_{err}}(t), \quad (6)$$

where T_{err} represents the time to occurrence of an error with the corresponding CDF given by $\mathrm{F}_{\mathrm{T}_{err}}(.)$.

f. Natural (external) hazards

Suppose that the external hazards occur according to a non-homogeneous Poisson process (NHPP) $\{\mathrm{N}(t): t \geq 0\}$ with intensity function $\mathrm{h}(t)$ and mean value function $\mathrm{H}(t)$, i.e.,

$$\mathrm{H}(t) = \int_0^t \mathrm{h}(y)dy, \ t \geq 0. \quad (7)$$

The probability that a rolling stock component fails within the time interval (0, t) due to a natural event is given by:

$$POF_6(t) = \Pr[\mathrm{N}(t) \geq 1] = 1 - e^{-\mathrm{H}(t)}. \quad (8)$$

The total probability of failure within the time interval (0, t), POF (t) is obtained by summing up the probabilities of component failure due to various root causes, i.e.,

$$\mathrm{POF}(t) = \sum_{i=1}^{6} POF_i(t). \quad (9)$$

Step 6. Determine the total consequences of a failure. Three cost factors are considered in this study as potential consequences of failure events. These include the costs of inspection, maintenance and repair (C_{IMR}), the penalty charges due to train delays or service interruption (C_P), and the costs of loss of reputation (or loss of fees) in relation to train cancellations (C_L). The time value of money has also to be taken into account in consequence analysis. The future value of cost factors at time t is given by:

$$\mathrm{C}(t) = (1+r)^t \times \mathrm{C}_0, \quad (10)$$

where C_0 represents the present value of cost factors and r (≥0) is the discount rate. Therefore, the discounted total cost of failure consequences at time t in the future is calculated by Eq. (11) as following:

$$\mathrm{COF}(t) = (1+r)^t \times [\mathrm{C}_{IMR} + \mathrm{C}_P + \mathrm{C}_L]. \quad (11)$$

Step 7. Calculate the total risk.

The risk of failure at time t, ROF(t) is quantified by multiplying the total probability that a failure occurs before time t and the total consequences of failure. Then,

$$\mathrm{ROF}(t) = \mathrm{POF}(t) \times \mathrm{COF}(t), \ t \geq 0. \quad (12)$$

Since the probability of occurrence and the cost consequences of a failure event increase over time, the associated risk of failure will be a continuous, increasing, nonlinear function of t.

Step 8. Develop a preventive maintenance (PM) programme based on risk measures.

The time-variant risk function in Eq. (12) is expressed in monetary term, and hence, it can be used for prioritization and scheduling of appropriate PM tasks. It is beneficial for a train company to carry out PM only when the reduction in discounted cost of risk of failure becomes greater than the cost of conducting a PM action on a non-failed component (C_{PM}). In order to determine the optimal time to conduct a PM action, a risk-cost function as below is defined that has to be minimized:

$$\mathrm{RC}(t) = \sum_{i=1}^{6} POF_i(t) \times (1+r)^t [\mathrm{C}_{IMR} + \mathrm{C}_P + \mathrm{C}_L] + \left[1 - \sum_{i=1}^{6} POF_i(t)\right] \times \mathrm{C}_{PM}, \ t \geq 0. \quad (13)$$

The problem is to find a time interval for PM actions that minimizes the risk-cost function RC(t) in Eq. (13); in other words, finding optimal decision variable T^* such that

$$\mathrm{RC}(\mathrm{T}^*) = \inf\{\mathrm{RC}(t); 0 < t \leq \mathrm{T}^\circ, \mathrm{RC}(0) = \mathrm{C}_{PM}\}. \quad (14)$$

Step 9. Compare the performance of the proposed inspection method with current practices.

Since the maintenance resources are released on a criticality basis and the PM tasks will be carried out ahead of unexpected failures, less time and cost are spent and less damage is likely to occur. In this step, the performance of the proposed inspection and maintenance method (in terms of life expectancy of rolling stock, whole life cost and reliability of transport service) is evaluated and compared with the currently used inspection methodologies including run-to-failure, periodic renewal, and reliability centered inspection. For this purpose, some advanced computational techniques like Monte-Carlo simulation (MCS) approach over the lifetime of rolling stock can be used (for more see Zio, 2013).

4 APPLICATION AND RESULTS

In this Section, the proposed risk-based inspection and maintenance model is applied to a pantograph system of the Class 380 electric multiple unit (EMU) that operates on the national railway network in Scotland (Brown, 2013; Dinmohammadi *et al.*, 2016). An analysis of performance data for the Class 380 EMUs shows that the pantograph failures are responsible for a large proportion of the train delays and cancellations. A pantograph system consists of several components among which nine ones are often more critical to the functionality of the rolling stock than the reminders (see Figure 5).

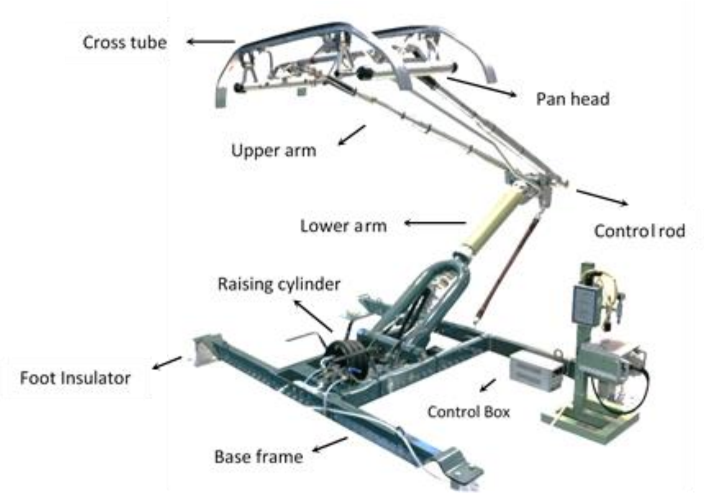

Figure 5. Major components of a train's pantograph system.

A pantograph system is subject to a number of complex potential failure modes that are related to mechanical structures, electrical units, pneumatic transmission, network control, etc. The major failure modes identified through an importance analysis are: cracks, breaks, fatigue, pitting, wear, and discharge breakdown. The data required for this study were collected from the literature as well as the company's maintenance management information system (MMIS). The train considered in this study has been in operation since 2011 and there were reported a total number of 65 failure events related to pantograph system over the first two years of service. In the company's MMIS, the failure root causes are identified by a primary (one letter) and a secondary (between one and three letters) code. The list of defect codes used for pantograph and collector equipment is shown below:

GA – Air cylinder
GB – Pantograph braids
GC – Pantograph carbons
GI – Insulators
GJ – Auto dropping device
GK – Auto drop insulator pipe work
GL – Leads/busbar connections
GM – Air motor
GP – Pantograph pipe work
GV – Pantograph control valves
GZF – Pantograph tested and no fault found

Figure 6 illustrates a bar chart which depicts the number of pantograph failures under each defect code in descending order.

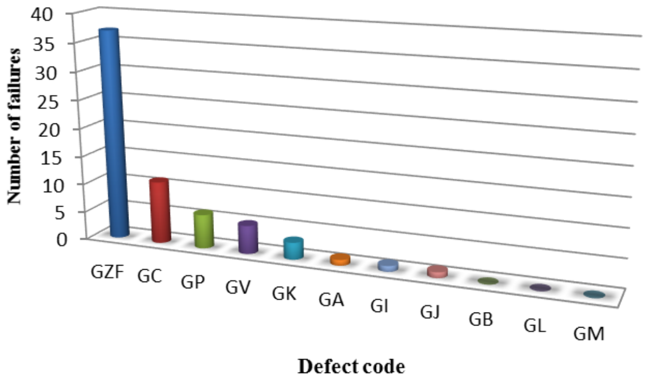

Figure 6. Number of failures under each defect code.

The delay information was extracted from a database system that is used for monitoring the progress of trains and tracking delays on Great Britain's rail network, called TRUST (TRain RUnning SysTem TOPS). The Class 380 train as a whole can be considered as a complex repairable system in which any failures found within sub-systems can be restored to a "as-good-as-new" condition through PM actions. As part of the franchise agreement, there is financial penalty imposed on the train operating company for every delay or cancellation. The pantograph failures resulted in a total of 2,523 minutes of delay, 123 full cancellations and 71 part-cancellations with the financial penalties of £50 per delay minute, £1000 for each full- and £500 for each part-cancellation. The annual discount rate is set equal to 3 percent.

Figure 7 shows that $T^* = 363$ hours with the corresponding risk-cost function $RC(T^*) = 6672.018$ is the optimal time interval for PM actions of the pantograph system. When compared to current practice of maintenance, the proposed risk-based inspection method can reduce the costs by 3.47%.

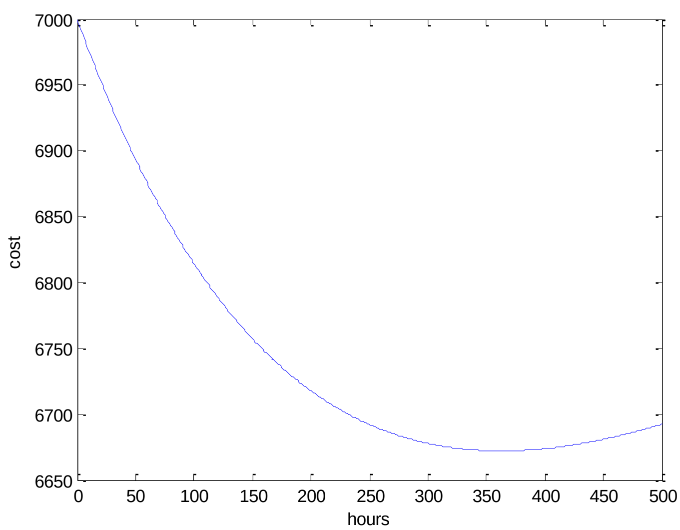

Figure 7. Risk-cost function; $T^* = 363$, $RC(T^*) = 6672.018$.

5 CONCLUSIONS

In this paper, a novel risk-based modelling approach for inspection and maintenance management of the railway rolling stock assets was presented. In this approach, the major failure modes of various rolling stock components as well as their common root causes were identified through an importance analysis and stochastic models were used to estimate the likelihood of occurrence of a failure. On the other side, the consequences of failures were calculated based on a discounted cost modelling that involved costs of inspection, maintenance and repair, the penalty charges due to train delays or service interruption, and the costs of loss of reputation in relation with train cancellations. A quantitative model was developed for assessing the time-variant risk associated with different types of failures by multiplying the total probability of failure and the total consequences of failure. The risk level of failure over time was used to prioritize and schedule the maintenance effort on a criticality basis. The model was applied to a rolling stock passenger door system in a Scottish train operating company and its performance was evaluated. The results indicate that the proposed risk-based inspection and maintenance modelling methodology has a substantial potential to reduce the life cycle costs while ensuring higher level of safety and service quality compared with the currently used inspection methodologies including run-to-failure, periodic renewal, and reliability centered inspection.

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