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Journal Name	Urban Rail Transit	
Corresponding Author	Family Name	**Dinmohammadi**
	Particle	
	Given Name	**Fateme**
	Suffix	
	Division	Department of Mechanical Engineering, School of Engineering and Built Environment
	Organization	Glasgow Caledonian University
	Address	Glasgow, UK
	Phone	
	Fax	
	Email	fateme.dinmohammadi@gcu.ac.uk
	URL	
	ORCID	
Author	Family Name	**Alkali**
	Particle	
	Given Name	**Babakalli**
	Suffix	
	Division	Department of Mechanical Engineering, School of Engineering and Built Environment
	Organization	Glasgow Caledonian University
	Address	Glasgow, UK
	Phone	
	Fax	
	Email	babakalli.alkali@gcu.ac.uk
	URL	
	ORCID	
Author	Family Name	**Shafiee**
	Particle	
	Given Name	**Mahmood**
	Suffix	
	Division	
	Organization	Cranfield University
	Address	College Road, Bedfordshire, MK43 0AL, UK
	Phone	
	Fax	

	Email	m.shafiee@cranfield.ac.uk
	URL	
	ORCID	
Author	Family Name	**Bérenguer**
	Particle	
	Given Name	**Christophe**
	Suffix	
	Division	GIPSA-lab
	Organization	Université Grenoble Alpes
	Address	Grenoble, France
	Division	GIPSA-lab
	Organization	CNRS
	Address	Grenoble, France
	Phone	
	Fax	
	Email	christophe.berenguer@gipsa-lab.grenoble-inp.fr
	URL	
	ORCID	
Author	Family Name	**Labib**
	Particle	
	Given Name	**Ashraf**
	Suffix	
	Division	
	Organization	University of Portsmouth
	Address	Portsmouth, PO1 3DE, UK
	Phone	
	Fax	
	Email	ashraf.labib@port.ac.uk
	URL	
	ORCID	

	Received	4 February 2016
Schedule	Revised	17 September 2016
	Accepted	22 September 2016

Abstract

Railway transport consists of two main asset classes of infrastructure and rolling stock. To date, there has been a great deal of interest in the study and analysis of failure mechanisms for railway infrastructure assets, e.g. tracks, sleepers, bridges, signalling system, electrical units, etc. However, few attempts have been made by researchers to develop failure criticality assessment models for rolling stock components. A rolling stock failure may cause delays and disruptions to transport services or even result in catastrophic derailment accidents. In this paper, the potential risks of unexpected failures occurring in rolling stock are identified, analysed and evaluated using a failure mode, effects and criticality analysis-based approach. The most critical failure modes in the system with respect to both reliability and economic criteria are reviewed, the levels of failure criticality are determined and possible methods for mitigation are provided. For the purpose of illustrating the risk evaluation methodology, a case study of the Class 380 train's door system operating on Scotland's railway network is provided and the results are discussed. The data required for the study are partly collected from the literature and unpublished sources and partly gathered from the maintenance management information system available in the company. The results of this study can be used not only for assessing the performance of current maintenance practices, but also to plan a cost-effective preventive maintenance (PM) programme for different components of rolling stock.

Keywords (separated by '-')	Railway rolling stock - Failure mode - Effects and criticality analysis (FMECA) - Risk evaluation - Preventive maintenance (PM)
Footnote Information	Editor: Xuesong Zhou

Urban Rail Transit
DOI 10.1007/s40864-016-0043-z
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Risk Evaluation of Railway Rolling Stock Failures Using FMECA Technique: A Case Study of Passenger Door System

Fateme Dinmohammadi[1] · Babakalli Alkali[1] · Mahmood Shafiee[2] · Christophe Bérenguer[3,4] · Ashraf Labib[5]

Received: 5 February 2016 / Revised: 17 September 2016 / Accepted: 22 September 2016
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Abstract Railway transport consists of two main asset classes of infrastructure and rolling stock. To date, there has been a great deal of interest in the study and analysis of failure mechanisms for railway infrastructure assets, e.g. tracks, sleepers, bridges, signalling system, electrical units, etc. However, few attempts have been made by researchers to develop failure criticality assessment models for rolling stock components. A rolling stock failure may cause delays and disruptions to transport services or even result in catastrophic derailment accidents. In this paper, the potential risks of unexpected failures occurring in rolling stock are identified, analysed and evaluated using a failure mode, effects and criticality analysis-based approach. The most critical failure modes in the system with respect to both reliability and economic criteria are reviewed, the levels of failure criticality are determined and possible methods for mitigation are provided. For the purpose of illustrating the risk evaluation methodology, a case study of the Class 380 train's door system operating on Scotland's railway network is provided and the results are discussed. The data required for the study are partly collected from the literature and unpublished sources and partly gathered from the maintenance management information system available in the company. The results of this study can be used not only for assessing the performance of current maintenance practices, but also to plan a cost-effective preventive maintenance (PM) programme for different components of rolling stock.

Keywords Railway rolling stock · Failure mode · Effects and criticality analysis (FMECA) · Risk evaluation · Preventive maintenance (PM)

1 Introduction

The railway transport sector is a key enabler of economic growth worldwide. The United Kingdom (UK) has a railway network of 17,732 km of track (the 17th largest in the world) which is spread over wide geographical areas throughout the country [1]. The number of railway passengers as well as freight volumes has increased significantly in recent years. According to recent statistics published by the Office of Rail and Road (ORR), a total of 1.654 billion journeys were made in 2014–2015, making the UK's railway network the fifth most used in the world [2]. The growth of journeys is partly attributed to a shift away from private motoring due to increasing road

✉ Fateme Dinmohammadi
fateme.dinmohammadi@gcu.ac.uk

Babakalli Alkali
babakalli.alkali@gcu.ac.uk

Mahmood Shafiee
m.shafiee@cranfield.ac.uk

Christophe Bérenguer
christophe.berenguer@gipsa-lab.grenoble-inp.fr

Ashraf Labib
ashraf.labib@port.ac.uk

1 Department of Mechanical Engineering, School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow, UK

2 Cranfield University, College Road, Bedfordshire MK43 0AL, UK

3 GIPSA-lab, Université Grenoble Alpes, Grenoble, France

4 GIPSA-lab, CNRS, Grenoble, France

5 University of Portsmouth, Portsmouth PO1 3DE, UK

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congestion, but also to the improved quality of railway transport services. The British railway industry was privatised over the period 1994–1997, but nowadays most of the railway tracks are managed by Network Rail (NR) [3]. Nevertheless, the network is still confronted with serious problems caused by premature failure of assets that require costly and time-consuming maintenance work.

The railway assets in general can be categorised into two types: The first one is the infrastructure which consists of fixed assets such as tracks, points and interlocking, bridges, signalling system, electrical units, etc. The other one is the rolling stock which includes assets that can move on railway, e.g. locomotives, passenger coaches, freight cars. A rolling stock is a multi-component system that consists of wheels, bogies, doors, power unit, brake control unit, coupler, compressor, pantograph, etc. Figure 1 illustrates the major components of a British Class 800 rolling stock asset and their relationships to one another. A failure of any of rolling stock components can cause a complete failure of the system and consequently lead to traffic delays and disruptions, passenger inconvenience and economic losses for train operating companies. Rolling stock failures may also result in the derailment of waggons and casualties of passengers and crew. For these reasons, it is crucial to develop practical methodologies for analysing and mitigating the risks associated with failure of various rolling stock components at a system level.

In recent years, a great deal of attention has been paid to the study of the failure/damage mechanisms for railway infrastructure assets. However, few attempts have been made by researchers to develop failure criticality assessment models for rolling stock components. There are several tools and techniques that are currently used to determine and evaluate the risk of failures occurring in engineering systems throughout their entire life cycle—from design to production, operation and maintenance. One of the widely used techniques in this regard is the failure mode, effects and criticality analysis (FMECA) which is an extended version of the failure mode and effects analysis (FMEA) method [4, 5]. In the FMECA technique, all potential failure modes that could occur in various components of a system are systematically analysed. The causes of each failure mode and their associated impact on system operation are identified. A "risk" or "criticality" measure is then calculated for each failure mode based on the rate of occurrence of failure and severity of the possible consequences. Finally, the failure modes are prioritised or classified according to their levels of criticality and some preventive actions are proposed to improve the reliability of the system.

In this paper, the potential risks of unexpected failures occurring in rolling stock are identified, analysed and evaluated using a FMECA-based approach. The criticality of a failure is measured as the product of the likelihood of occurrence of the failure mode (O) and the severity of damage caused by the failure (S), where O and S are allocated numbers from 1 to 10. According to criticality levels ranging from 1 (lowest) to 100 (highest), the most critical failure modes in the rolling stock with respect to both reliability and economic criteria are identified. Finally, several potential protective measures to eliminate the root causes of rolling stock failures are provided. The

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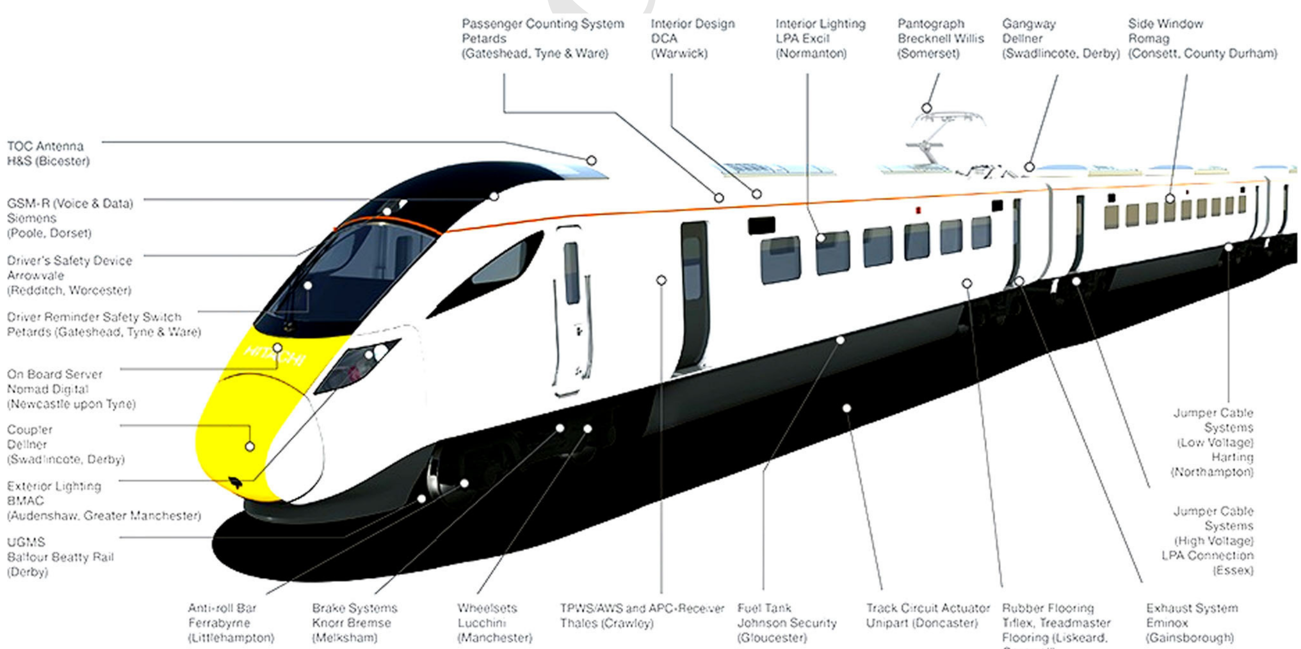

Fig. 1 Railway rolling stock components (www.hitachirail-eu.com)

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presented model is applied to a rolling stock passenger door system in a Scottish train operating company and the results are discussed.

The remainder of this paper is organised as follows. Section 2 gives a brief overview of the risk evaluation in the railway industry. Section 3 presents a FMECA methodology for risk evaluation of rolling stock failures. In Sect. 4, a case study of the passenger train door system is described and the results are presented in detail. Finally, the paper is concluded in Sect. 5.

2 Risk Assessment in the Railway Industry

As stated in ISO 31000:2009 [6], 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: (i) the probability of occurrence of a failure and (ii) the magnitude of the consequences of the failure.

Risk analysis is defined as a systematic use of available information to characterise 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 further actions can be taken to reduce and mitigate the most critical ones where resources are limited. Risk analysis can be either qualitative or quantitative or a combination of both. The qualitative risk evaluation methods use the judgement and opinions of knowledgeable experts to categorise 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 the qualitative ones. However, the data requirements for quantitative risk assessment techniques are higher, which makes them difficult to apply.

In the last decade, many studies have been carried out to analyse the likelihood of failure of railway assets as well as to evaluate the impact of a failure on transport operations. Several risk assessment tools and techniques have been used for this purpose, including root cause analysis (RCA), fault tree analysis (FTA), event tree analysis (ETA), Weibull analysis, human reliability assessment (HRA), etc. In what follows, we briefly review the most relevant, recent works on the subject below.

Haile [7] identified the strengths and weaknesses of the quantitative risk analysis (QRA) technique in application to railway system design and operation. Carretero et al. [8], Garcia Marquez et al. [9] and Pedregal et al. [10] used a Reliability Centred Maintenance (RCM) methodology for failure analysis of railway infrastructure assets. Podofillini et al. [11] developed a model to calculate the risks and costs associated with inspection of railway tracks. Zio et al. [12] proposed a risk-informed approach for improving the service level of railway networks as well as maintaining high standards of safety. Their approach uses importance measures to identify those sections of the network having the highest impact on the overall trains' delay. Kumar et al. [13] developed an approach for risk assessment of railway defects that can be used to support the decision-making process for scheduling of railway inspection and grinding activities based on the type and the risk of defect. Macchi et al. [14] presented a two-stage methodology for maintenance management of the railway infrastructures. The first step of this methodology consists of a family-based approach for the equipment reliability analysis and the second step builds a reliability model for the railway system in order to identify the most critical items. Cheng et al. [15] applied the FMECA method to analyse the reliability of metro door systems. Kim and Jeong [16] used the FMECA method to evaluate the consequences of brake system failure in a railroad vehicle and then analysed the adequacy of preventive maintenance (PM) programmes for the asset. Recently, Rahbar and Bagheri [17] presented a framework to evaluate the risks associated with moving hazardous materials (hazmat) by rail transport.

As the review shows, very few studies assessing the criticality of railway rolling stock component failures and the subsequent impacts on infrastructure services have been conducted so far. In what follows, we propose a FMECA-based methodology to determine the criticality level of failures occurring in rolling stock assets.

3 FMECA Methodology to Rolling Stocks

The proposed methodology for risk evaluation of rolling stock failures, as shown in Fig. 2, includes nine steps. These steps are described in detail as follows:

Step 1 Select a rolling stock component for the study

A railway rolling stock is usually composed of two main parts, namely car body and bogie parts, each consisting of different components and each performing certain essential function(s). The main rolling stock components that can be considered for risk analysis study include (but not limited to) the following:

- *Door unit* The train doors are "opened and "closed" at each station to allow passengers to enter or leave the coach.
- *Scroll compressor* It is a certain type of compressor used for HVAC and brake systems to compress air.
- *Bogie* It is a framework carrying either four or six wheels attached to the coaches.

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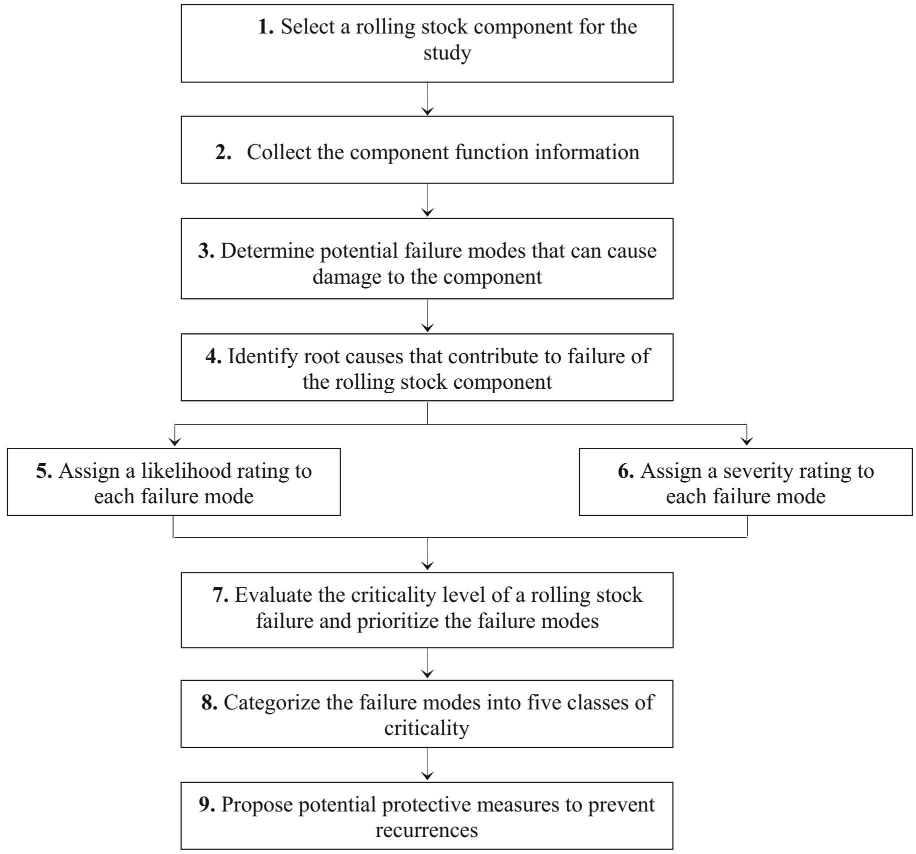

Fig. 2 Risk evaluation methodology for railway rolling stock failures

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- *Pantograph* It is a device mounted on the roof of the train to collect electric current from overhead lines.
- *Coupling system* A coupler is a device used for connecting rolling stocks in a train.
- *Braking unit* It is used in order to decrease velocity of trains, enable deceleration, control acceleration and keep them fix when parked.
- *Air spring suspension* It gives a better ride and the pressure can be adjusted automatically to compensate for additions or reductions in passenger loads.
- *Heating ventilation and air conditioning (HVAC)* It provides fluid air through the facility providing either hot or cool air dependent on the desired temperature.

Step 2 Collect the component function information

As each of the components' functions in rolling stock is different, the mechanism of the occurrence of failure will be different from one component to another. The risk analysts must have a good understanding of the components of the system and the way in which they interact with each other and with their surrounding environment. The component function information can be collected by answering some of the following 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?

In order to define the logical interaction of components within the rolling stock, a Reliability Block Diagram (RBD) can be useful. An RBD is a diagrammatic method for showing how components' reliability contributes to the success or failure of a complex system. Each block represents a component of the system with a certain probability of failure or failure rate. The blocks are often configured (i.e. interconnected) in series structure, parallel structure, k-out-of-n structure, etc. [18]. In a series structure, the entire system will fail if one of the components fails. A parallel structure is used to show redundancy wherein the whole system can function properly as long as at least one component is working properly. For k-out-of-n structures, a system is considered functioning if at least k out of a total of n components are working properly ($1 < k < n$). As an example, the RBD of a railway train passenger door system is shown in Fig. 3.

Step 3 Determine potential failure modes that can cause damage to the component through reviewing past failures

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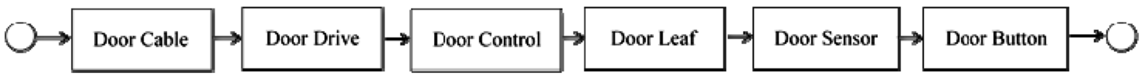

Fig. 3 A reliability block diagram for the rail train passenger door system

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The identification of potential failure modes is an important part of the risk analysis studies. For each component chosen, there exist some failure modes that can be determined by reviewing past failures, inspection records and non-destructive testing (NDT) measurements. The major failure modes in rolling stock components include disconnection, fracture, fatigue, cracked, degraded, deformed, stripped, worn, corroded, binding, leaking, buckled, sag, loose, misalignment and obstruct. Any of these failure modes or their combination can cause rolling stock to fail. For some rolling stock components, more than one failure mode may be present.

Step 4 Identify root causes that contribute to failure of the rolling stock component through interviewing experts from various fields

After all the failure modes have been identified, the risk analysts begin to investigate what, how and why a failure happened, thus preventing recurrence. The failure root causes can be determined by interviewing experts including designers, train operators, inspectors, maintenance technicians, etc. and using some analytical techniques like Root Cause Analysis (RCA) and Fault-Tree Analysis (FTA) [19]. RCA is a useful process that helps analysts identify and understand the initiating causes of a failure. FTA is a top-down and deductive failure analysis method through which all undesired events that may lead to system failure are analysed.

Some common root causes of the rolling stock failures are electrical/mechanical overloading, installation failure, software failure, hardware failure, material defects are calibration errors. 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. Assign a likelihood rating to each failure mode of the rolling stock component

The failure data are analysed using statistical techniques (e.g. Weibull analysis, regression models, data mining) to create models for estimation of the likelihood of rolling stock defects. The likelihood of occurrence of a failure is evaluated on the basis of failure rates (in year) estimated from historical data or expert knowledge. The failure rate of the failure mode i is estimated by

$$\lambda i = \frac{\text{Total number of failures resulting mode i since installation time}}{\text{Duration of time (in years) operation}}. \quad (1)$$

Based on the failure rates obtained, a likelihood of occurrence rating based on a 10-point scale is assigned to each failure mode (see Table 1). As shown, the recommended likelihood rating scale varies from 1 to 10, where 1 represents "remote" and 10 indicates "almost certain".

Step 6 Assign a severity (consequence) rating to each failure mode of the rolling stock component

Each of the possible failure modes on rolling stock components has different impacts on train safety, transport operations as well as the environment. The failure consequences of a rolling stock component can be addressed from the following points of view throughout the service life-cycle:

- *Economic impacts* Costs of inspection, maintenance and renewal (IMR), and penalty charges due to train delays or cancellation;
- *Social impacts* Passengers' dissatisfaction caused by service interruptions;
- *Safety impacts* Fatalities or injuries due to train derailment;
- *Environmental impacts* Greenhouse damages, chemical spills, etc.

In this study, the severity of failure is evaluated in terms of economic, social and safety losses and is described on a 10-point scale where 1 represents "no effect" and 10 indicates "dangerous without warning". The recommended severity rating scale is presented in Table 2.

Step 7 Evaluate the criticality level of a rolling stock failure and prioritise the failure modes in descending order

Table 1 Likelihood ratings for a failure in railway rolling stock

Rate	Likelihood	Criteria	Failure rate (/year)
1	Remote	Failure is unlikely to occur	1 in 1500,000
2	Very low	Very few failures occur	1 in 150,000
3	Low	Few failures occur	1 in 15,000
4	Moderate	Failures occur occasionally	1 in 2000
5			1 in 400
6			1 in 80
7	High	Failures occur frequently	1 in 20
8			1 in 8
9	Very High	Failures occur persistently	1 in 3
10			1 in 2

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Table 2 Severity ratings for a failure in railway rolling stock

Rating	Effect	Criteria	Severity of effect
1	None	No disruption	No effect
2	Very minor	Minor disruption to rail services	An inspection is carried out. Failure is noticed by few passengers
3	Minor		An inspection is carried out. Failure is noticed by average passengers
4	Very low		An inspection is carried out. Failure is noticed by most of the passengers but it does not discomfort them
5	Low	Some disruption to rail services	A repair action is necessary. Failure is noticed by most of the passengers and they experience some discomfort
6	Moderate		A repair action is necessary. Failure is noticed by all passengers and they experience discomfort
7	High		A repair action is necessary. Passengers are dissatisfied
8	Very high	Major disruption to rail services	The failed item needs to be replaced by a new one. Passengers are very dissatisfied
9	Dangerous with warning	May endanger rolling stock or passengers	The failure affects transport safety with warning and it involves noncompliance with regulation
10	Dangerous without warning		The failure mode affects transport safety without warning and it involves noncompliance with regulation

The criticality level of a rolling stock failure is defined by a risk factor (R) which is calculated by multiplying the likelihood rating (O) by the impact rating (S), i.e.

$$R = O \times S. \tag{2}$$

Since the likelihood of occurrence and the severity of damage have rating values between 1 and 10, the risk factor R will range from 1 to 100. The risk factors obtained for all failure modes are prioritised in descending order and the most critical ones with respect to both reliability and damage severity are identified. The most critical failure modes will be the ones occurring most frequently and leading to largest losses.

Step 8. Categorise the failure modes into five classes of criticality

The failure modes according to the level of their criticality are categorised into five classes, namely very low, low, medium, high and very high critical. These classes of failure criticality and the associated improvement actions are described in Table 3. A failure mode will be very low critical when its risk factor is between 1 and 4, will be low critical when the risk factor is between 5 and 9, will be medium critical when the risk factor is between 10 and 25, high critical when its risk factor is between 26 and 49, and very high critical when the risk factor is between 50 and 100.

Obviously, the criticality classes defined in Table 3 can vary depending on the type of rolling stock, available maintenance resources, safety standards, railway operations, traffic density, train speed, etc. The completed criticality matrix provides a useful, graphical portrayal of the risk factors obtained from the analysis. Different regions of the criticality matrix represent different levels of criticality for rolling stock components. For example, as shown in Fig. 4, the red cells at the top right-hand corner of the matrix represent "very high critical" region, whilst the green cells at the bottom left-hand corner represent "very low critical" region.

Step 9. Propose potential protective measures to prevent recurrences

In order to achieve an acceptable level of criticality and enhance the reliability of the system, some improvement actions need to be proposed or initiated for medium, high and very high critical failure modes and components.

Table 3 Five classes of failure criticality and the associated improvement actions

Criticality level	Risk Factor (R)	Recommendation
Very low	$1 \leq R \leq 4$	Almost unnecessary to take the improvement actions
Low	$5 \leq R \leq 9$	Minor priority to take the improvement actions
Medium	$10 \leq R \leq 25$	Moderate priority to take the improvement actions
High	$26 \leq R \leq 49$	High priority to take the improvement actions
Very high	$50 \leq R \leq 100$	Absolute necessary to take the improvement actions.

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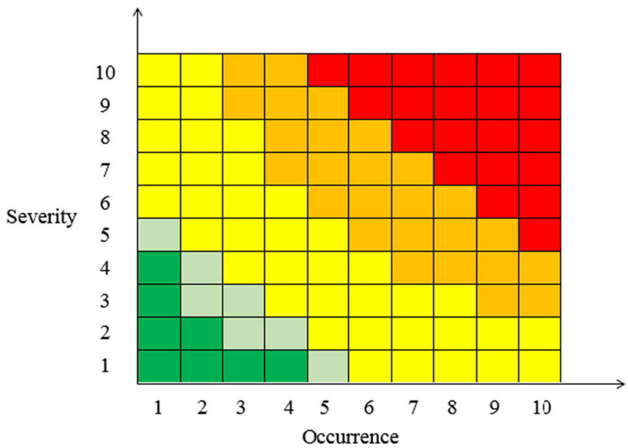

Fig. 4 A criticality matrix for rolling stock failures

Generally, the following protective measures can be considered to achieve a lower level of risk of failure in railway rolling stocks:

- improving the reliability of individual components (parts improvement method);
- adding redundancy to critical components in order to increase the mean time between failures (MTBF);
- planning and undertaking scheduled cost-effective maintenance activities to minimise interruptions to railway transport services (e.g. see [20]);
- utilising sensor-based technologies to continuously monitor the behaviour of rolling stock components; and
- minimising the service disruption through shortening the repair lead times [21].

4 Application to Passenger Door Unit

In this section, the proposed risk evaluation model is applied to a passenger door system of the Class 380 electric multiple unit (EMU) that operates on the national railway network in Scotland [22]. The Class 380 trains are some of the newest and most advanced fleets available on the market, which account for around 10 % of the total number of trains operating on Scotland's railway network. These trains have spacious seating, wide aisles, roof-mounted air conditioning, 230 V power sockets for laptops and hand-held devices under each table, ample luggage provision, dedicated areas for cycles and wheelchairs, and Closed Circuit Television (CCTV) for added security.

There are several key components on the Class 380 trains that are often far more critical to the functionality of the system than the others. An analysis of performance data indicates that a great number of failures are associated with door system (see Fig. 5), having a detrimental effect on the train reliability and consequentially passenger satisfaction. A door system consists of the following major components:

Fig. 5 The Class 380 train's passenger door unit

- *Door drive* Gearbox, upper locking devices, synchronising cable and guides;
- *Control elements and switches* Open/close limit switches and pushbuttons;
- *Door leaf* Mounting of leaf, window and lead-mounted guides;
- *Safety and emergency devices* Mechanical switches, finger protection and light barrier;
- *Other components* Interior panelling, wiring, lighting and steps.

The data required for this study were collected from the literature, the company's maintenance management software system called EQUINOX and the UK's railway performance management software DATASYS BUGLE [23]. These systems not only monitor all maintenance activities carried out by sub-contractors, but also record the trains' activities from the operations side of business.

A fleet of 38 Class 380 trains (including 22 trains with four cars and 16 trains with three cars) is considered for this study. These trains are in operation since early December 2010 and have experienced a total of 2493 failures within the duration of this study. Of these, 205 failures (i.e. 8.2 % of the total failures) were related to defects associated with door unit components. The total mileage that these trains have been in operation is 2,235,312 miles. Therefore, the mean number of failures (MNF) per train and the mean mileage between failures (MMBF) associated with door unit are given by

$$\mathrm{MNF} = \frac{205}{38} = 5.394;\ \mathrm{MMBF} = \frac{2,235,512}{38} = 58,824\ \text{miles}.$$

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The five why's technique was used to identify the potential failure modes and determine the root causes of failures. An example of the technique applied to the door system is given below:

Door system on class 380 train does not operate
↳ There is no electrical supply
Why? ↳ Miniature circuit breaker (MCB) was found tripped
Why? ↳ Electrical plug which supplied the motor is not fully secured
Why? ↳ There is no means of secondary locking on the 40 pin plug
Why? ↳ Fault in the design of the plug.
Why?

The results of the analysis show that the door defects are due to twelve primary sources (root causes), as illustrated in Fig. 6. These, in order, are given as follows:

a. *No fault found (NFF)* No particular root cause was found for 87 door defects (i.e. 42.4 % of the total door defects reported).
b. *Faulty push buttons* These were found to be the cause of 39 door defects (i.e. 19 % of the total door defects reported).
c. *Faulty door control unit (DCU)* There have been 20 failures recorded with failure modes such as internal power supply failure, internal obstruction detection due to motor voltage and also falshcodes on DCU.
d. *Mechanical failures* 18 failures were reported to be in relation to actuator rods becoming loose or not disengaging from limit switches.
e. *Light barrier* There have been seven failures due to light barrier.
f. *Door drive* There have been 6 failures in relation to door drive of the system. These failures are due to different reasons such as motor failure, encoder failure and faulty connections to the drive system.
g. *Guard operating panel (GOP)* six failures were found to be due to GOP defects.
h. *Limit switches* there have six faults occurred in relation to limit or micro-switches on the drive system.

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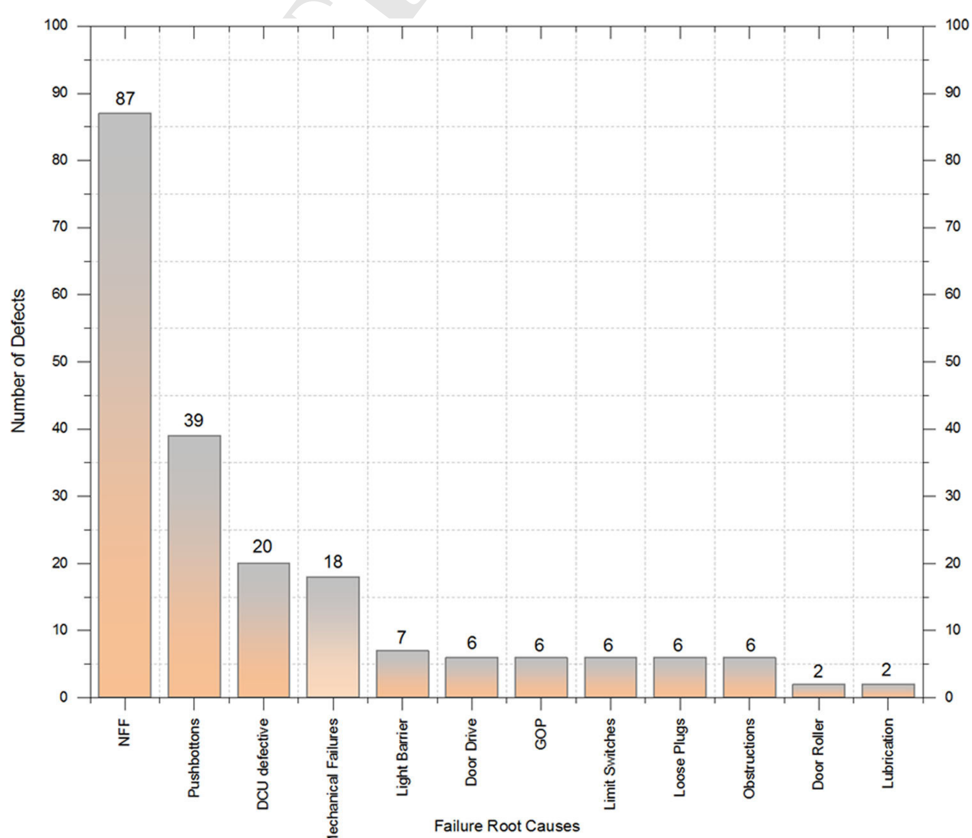
Fig. 6 Failure mode frequencies for a passenger door system



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i. *Loose plugs* Six failures were found to be due to loose plugs or loose connections within the plugs themselves.
j. *Obstructions* There have been six failures of door obstruction of the door leaves themselves, mostly due to dirt or debris stuck in door tracks.
k. *Door roller* two failures were reported to be due to the rollers becoming detached from housing and not tough due to being damaged.
l. *Lubrication* There have been two failures as a result of poor lubrication on the door system.

Table 4 presents the frequency of door system defects occurred in each train due to the above-mentioned 12 failure root causes.

Qualitative assessment of the severity of different types of door defects was performed based on the negative impacts on transport services in terms of train delays, speed restriction and service cancellation. The delay information was extracted from a database system called TRUST (TRain RUnning SysTem TOPS) that is used for monitoring the progress of trains and tracking delays on the UK's railway network. The total delay time of the train due to door defects was 518 min. The train operating company is penalised £50 per minute delay in service. Thus, the total penalty charges due to train delays will be 518 min × £50/min = £25900.

A Delphi technique was used to elicit the experts' estimates of the failure likelihood and damage severity. Three academics who have published several papers in the field of risk and reliability, three maintenance engineers from the operating company with over 15 years of experience, one designer from the design consultancy and one designer from the manufacturer company were involved in this FMECA study. The results of the risk evaluation for the rolling stock door system are given in a worksheet format in Table 5. As shown, the level of criticality for various failure modes ranges from 3 to 28, where less than three percent of the failure modes fall into "very low critical" category, around 15 % of the failure modes are classified as "low critical", around 70 % of the failure modes are "medium critical" and 12 % of the failure modes fall into "high critical" category. The high critical failure mode includes nine items, of which four failure modes have the risk factor of 27 and five failure modes have a criticality of 28 (out of 100). To avoid the recurrence of these failure modes, it is crucial to plan and carry out PM actions in a cost-effective and timely manner.

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The Class 380 trains are expected to run 160,000 miles per year and to be in operation for 300 days of the year. Thus, the average daily miles for each train will be 533 miles. The current maintenance programme includes eleven tasks as described in Table 6 [24].

The current maintenance activities were selected according to the original equipment manufacturer (OEM)'s recommendations as well as using the experience of other fleets. It was found that when previous fleets were introduced in the UK's railway network, too much intrusive maintenance was undertaken and thus led to excessive delays. However, the Class 380 has different doors in the sense that they are electrically powered and the older fleets have pneumatic operations. The controls of the pneumatic system can be adjusted, which was found to cause problems, and the technology at time of manufacture was not sufficient to fit tamper-proof components. Overall, the current maintenance programme is not adequate and in order to reduce the number of door-related defects, a new PM programme including fourteen tasks has been proposed by company's asset management team (see Table 7).

Table 4 Frequency of door defects in each train due to various root causes

Train	Failure root causes												Total
	NFF	Pushbutton	DCU	Mechanical failures	Light barrier	Door drive	GOP	Limit switches	Loose plugs	Obstructions	Door roller	Lubrication	
1	2	4	0	2	1	0	1	0	2	1	0	0	13
2	7	3	0	2	0	1	0	0	0	0	0	0	13
3	8	1	0	0	0	0	0	1	0	2	0	0	12
4	4	1	2	0	1	1	0	0	0	0	1	0	10
5	0	2	2	2	0	0	0	2	0	0	0	1	9
6	3	0	1	1	1	0	0	0	0	0	0	0	6
…	…	…	…	…	…	…	…	…	…	…	…	…	…
38	…	…	…	…	…	…	…	…	…	…	…	…	1
Total	87	39	20	18	7	6	6	6	6	6	2	2	205

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Table 5 Risk evaluation results for the Class 380 train's door system

No	Item	Sub-item		Function	Failure modes	Potential causes	O	Potential effects	S	R
1	Door drive	A	Motor and gearbox	To drive spindle and locking shaft	No drive to spindle and locking shaft	Electrical failure of motor, wiring cut-out	**4**	Door will not open or close automatically, door can be moved with higher force manually	**7**	**28**
					No drive to spindle and locking shaft	Mechanical failure of assembly, fracture or loose fixings	**2**	Door blocked in open position, door cannot be closed and locked manually	**8**	**16**
					No drive to spindle and locking shaft	Mechanical failure of assembly, fracture or loose fixings	**2**	Door blocked in closed position, door does not open, also case in emergency	**9**	**18**
		B	Guide roller	To support the in/outward movement of the drive unit	Seised at door opening/closing	Mechanical failure of assembly	**3**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**12**
					Fractured at door opening/closing	Pollution U-Shape	**5**	Difficult door movement, exceeding opening and closing times	**4**	**20**
		C	Locking devices (locking shaft, compression spring, lock roller)	To lock/unlock the door leaf	Locking not possible	Deformation of locking roller, structural defect	**2**	Door is closed but not locked, door can be locked manually, door must be locked out of use	**7**	**14**
					Unlocking not possible	Deformation of locking roller, structural defect	**2**	Door is blocked in locked position, difficult door movement, door can be locked manually – out of use	**7**	**14**
		D	Coupling	To transmit motor movement to the driving device	No transmission	Fracture due to wear, ageing, loose fixings	**3**	Door will not open or close automatically, door can be moved with higher force manually, door can be locked out of use	**7**	**21**
		E	Spindle including bearing and spindle nut	To perform the door leaf translation	No performance, door blocked in open position	Mechanical failure of assembly, fracture or loose fixings	**3**	Door blocked in open position, door cannot be closed and locked manually	**8**	**24**
					No performance, door blocked in closed position	Mechanical failure of assembly, fracture or loose fixings	**3**	Door blocked in closed position, door does not open, also case in emergency	**9**	**27**
		F	Guide roller, support rail actuator-RH/LH	To provide/guide door movement during plug in/out movement	Sesed at door opening/closing	Mechanical failure	**2**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**8**
					Fractured at door opening/closing	Pollution U-Shape	**5**	Difficult door movement, exceeding opening and closing times	**4**	**20**

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Table 5 continued

No	Item	Sub-item		Function	Failure modes	Potential causes	O	Potential effects	S	R
		G	Bump stop, support rail actuator-RH/LH	To absorb opening impact	Fractured/Deformed at door opening	Ageing, structural defect	**3**	Damage of locking roller, excessive noise	**7**	**21**
		H	Synchronising Cable, support rail actuator-RH/LH	To synchronise the drive of right and door leaves	Ripped or elongated	Fatigue or corrosion	**3**	Door leaf movement not synchronised, difficult door movement, exceeding opening and closing times	**4**	**12**
		I	Guiding plate	To provide/guide door movement during plug in/out movement	Rough surface at door opening/closing	Mechanical failure	**3**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**12**
					Deformed at door opening/closing	Heavy mechanical failure	**2**	Door blocked, in case of emergency Door does not open	**9**	**18**
2	Door control elements and switches	A	Door control unit with bus coupler card-MVB	To realise automatic operation of the door, process signal inputs, control signal outputs, status and diagnostic messages Also to protect against unintended opening via the safety relay	Door does not open in closed and locked position	Defective DCU hardware, no power supply	**4**	No electrical opening, door must be locked, door must be locked out of use	**7**	**28**
					Door does not close in open position	Defective DCU hardware, no power supply	**4**	No electrical closing, door can be moved with higher force manually, door must be locked, door must be locked out of use	**7**	**28**
					Unintended door open command	DCU software malfunction	**1**	Door does not open if no hardwired release signal active due to safety relay, doors opens unintended if hardwired release signal active, not safety critical	**5**	**5**
		B	Switch left and right door leaf closed, S7/S8	To transmit door closed information to DCU	No transmission	Sensor defect, loose fixings, oxidisation of contacts	**3**	DCU has no closed signal, door must be locked manually, door must be locked out of use	**7**	**21**
					Permanent transmission	Sensor defect, short circuit, external voltage	**2**	Door has closed signal and also door open signal, door must be locked manually, door must be locked out of use	**7**	**14**
		C	Switch door out of use, S4	To transmit door locked out of use information to DCU and to bypass safety loop	No Transmission/bypass	Sensor defect, loose fixings, oxidisation of contacts	**3**	DCU has no locked signal, impossible to lock the door in case of a failure	**8**	**24**
					Permanent transmission/bypass	Sensor defect, short circuit, external voltage	**2**	DCU has locked signal and also door open signal, door must be locked manually, door must be locked out of use	**7**	**14**
		D	Limit switch door locked, S1/S2	To transmit door lock information to DCU	No transmission	Sensor defect, loose fixings, oxidisation of contacts	**3**	DCU has no locked signal, door must be locked manually, door must be locked out of use	**7**	**21**

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Table 5 continued

No	Item	Sub-item	Function	Failure modes	Potential causes	O	Potential effects	S	R
				Permanent Transmission	Sensor defect, short circuit, external voltage	2	DCU has locked signal and also door open signal, door must be locked manually, door must be locked out of use	7	14
	E	Service Toggle switch, S6, wiring harness	To disconnect supply voltage from door system, for maintenance purposes	Contact does not interrupt power supply permanently	Sensor defect, loose fixings, oxidisation of contacts	3	Exceed of maintenance efforts	1	3
				Contact interrupts power supply permanently	Sensor defect, loose fixings, oxidisation of contacts	3	No power supply at affected door, no automatic door movement, door must be locked out of use	7	21
	F	Door open pushbutton	To transmit opening order from passengers	No transmission	Sensor defect, wiring interruption, tightening not suitable	3	Door cannot be opened by passengers, passenger discomfort, door shall be locked, door must be locked out of use	7	21
				Permanent transmission	Sensor defect, contact fails closed	3	Doors open always at the stations, door shall be locked, door must be locked out of use	7	21
				Unintended transmission	Vibrations, spurious shortage	3	Spurious opening at the stations when door release is present, without release no effect	5	15
	G	Door close pushbutton	To transmit closing order from passengers	No transmission	Sensor defect, wiring interruption, tightening not suitable	3	Door cannot be closed by passengers, door closes only automatically	2	6
				Permanent transmission	Sensor defect, contact fails closed	3	Door cannot be opened by passengers, passenger discomfort, door shall be locked, door must be locked out of use	7	21
				Unintended transmission	Vibrations, spurious shortage	3	Spurious closing at the stations when door release, is present, without release no effect	1	3
	H	Switch emergency device, S3	To transmit emergency actuation information to DCU	No transmission	Sensor defect, loose fixings, oxidisation of contacts	3	Emergency actuation is not seen by DCU	9	27
				Permanent transmission	Sensor defect, short circuit, external voltage	3	After reset of handle, signal is still active Door must be locked manually, door must be locked out of use	7	21

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Table 5 continued

No	Item	Sub-item	Function	Failure modes	Potential causes	O	Potential effects	S	R
3	Door leaf	A Door leaf—L & R	To protect passenger from exterior environment	No protection	Heavy structural defect, loose of fixings	**2**	Loss of door leaf, passengers could fall out train	**10**	**20**
		B Window	To permit view from/to inside of the train	Bad or no view	Scratch or contaminated glass	**4**	Due to bad view for passengers, potentially longer dwell times	**4**	**16**
		C Linear ball track	To allow movement of the door leaves	Bad guidance	Mechanical failure	**3**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**12**
				Bad guidance	Pollution U-Shape	**5**	Difficult door movement, exceeding opening and closing times	**4**	**20**
				No guidance, blocked	Dogged U-Shape	**3**	Door blocked in open position, door cannot be closed and locked manually	**8**	**24**
		D Lower guide rail	To guide door leaf	Bad guidance	Mechanical failure	**3**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**12**
				Bad guidance	Pollution U-Shape	**5**	Difficult door movement, exceeding opening and closing times	**4**	**20**
				No guidance, blocked	Dogged U-Shape	**3**	Door blocked in open position, door cannot be closed and locked manually	**8**	**24**
		E Bottom active Locking	To support door leaf during movement	Bad guidance	Mechanical failure	**3**	Excessive noise, door leaf vibrations and exceeding opening and closing times	**4**	**12**
				Bad guidance	Pollution U-Shape	**5**	Difficult door movement, exceeding opening and closing times	**4**	**20**
				No guidance, blocked	Dogged U-Shape	**3**	Door blocked in open position, door cannot be closed and locked manually	**8**	**24**
			To provide over centre lock of door leaf a button	Locking not possible	Deformation of locking roller, structural defect	**2**	Door is closed but not locked, door can be locked manually, door must be locked out of use	**7**	**14**
				Unlocking not possible	Deformation of locking roller, structural defect	**2**	Door is blocked in locked position, difficult door movement, door can be locked manually—out of use	**7**	**14**

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Table 5 continued

No	Item	Sub-item	Function	Failure modes	Potential causes	O	Potential effects	S	R
4	Safety and emergency devices	A Lock out of use Device	To lock out the door manually in case of failure	No locking possible	Mechanical failure—fracture or loose fixings	**2**	Impossible to actuate the lock out of use device, door cannot be locked	**8**	**16**
				Unintended locking, in open position	Mechanical failure—fracture or loose fixings	**2**	Door cannot be closed and locked due to collision with locking arm	**8**	**16**
				Unintended locking, in closed position	Mechanical failure—fracture or loose fixings	**2**	Door is closed and locked, door cannot be opened	**6**	**12**
				Unintended unlocking of door locked out of use in closed position	Heavy mechanical failure—fracture, loose fixings	**2**	Loss of lock out of use position, door loop bypass will be interrupted If door opens unintended door loop will be activated and emergency brake will apply	**10**	**20**
		B Internal emergency unlocking device including bowden cable	To unlock the inside manually in case of emergency	No unlocking possible	Mechanical failure—fracture or loose fixings, extended Bowden cable	**3**	Impossible to actuate the lock out of use device, door cannot be unlocked and opened in case of emergency	**9**	**27**
				Unintended unlocking in opened position	Mechanical failure—fracture or loose fixings	**2**	Door is open, no effects After next closing, the may fail, door must be locked out of use	**7**	**14**
		C External emergency unlocking device including bowden cable	To unlock the door outside manually in case of emergency	No unlocking possible	Mechanical failure—fracture or loose fixings, extended Bowden cable	**3**	Impossible to actuate the lock out of use device, door cannot be unlocked and opened in case of emergency	**9**	**27**
				Unintended unlocking in opened position	Mechanical failure—fracture or loose fixings	**2**	Door is open, no effects After next closing, the may fail, door must be locked out of use	**7**	**14**
		D Light sensor	To detect entry and exit of passengers	No detection	Vandalism, sensor defective	**4**	Passenger could be striked by closing door, passenger must be injured, re-opening of the door due to motor current measurement	**7**	**28**
				Permanent detection	Short circuit, external voltage	**3**	Door reopens several times and stays free Door must be closed manually and locked out of use	**7**	**21**
		E Finger protection profile including sensitive edge	To ensure tightness between door leaves and between car body and door leaves	Poor tightness	Ageing, wearing	**4**	Excessive noise, pressure waves	**3**	**12**
				No tightness	Defective assembling	**2**	Sharp edges, passenger might be injured	**7**	**14**

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Table 5 continued

No	Item	Sub-item	Function	Failure modes	Potential causes	O	Potential effects	S	R
			To detect obstacles when closing	No detection	Vandalism, door edge sensor defect, non-stop signal	**4**	Reduction of redundancy for detection of objects, passenger injury	**7**	**28**
				Permanent detection	Short circuit, external voltage	**3**	Door reopens several times and stays free Door must be closed manually and locked out of use	**7**	**21**
		F Warning buzzer, H3	To warn passengers that the door should close automatically	No warning	Buzzer/light defective, wiring interruption	**3**	Passenger injury by closing door	**7**	**21**
				Permanent warning	Short circuit, external voltage	**3**	Permanent noise, passenger discomfort, door should be locked out of use	**7**	**21**
		G Warning Light, H4	To signal that the door is out of use	No light	Light defect, wiring interruption, tightening not suitable	**3**	Passengers could think the door is in use but door is not functioning, passenger discomfort	**3**	**9**
					Short circuit, external voltage	**3**	Passengers could think the door is out of use but door is functioning	**2**	**6**
5	Other components	A Interior panelling, door drive cover	To protect and cover cabling	No protection	Roof flap loosen, square key switch not locked or is defective	**2**	Risk of injury to passengers	**7**	**14**
		B Interior panelling, door leaves covers	To protect and cover cabling	No protection	Roof flap loosen, square key switch not locked or is defective	**2**	Risk of injury to passengers	**7**	**14**
		C Guard operating Panel, GOP	To locally control doors and communicate with the driver	No control/no communication	Electrical defect	**4**	Door is in function but GOP is not, guard must use other GOP	**2**	**8**
		D Wiring/cabling assembly	To guide and protect the electrical wire	Damaged wiring	Ageing, wearing of energy chain	**3**	Broken wire, loss of function, door must be locked manually	**6**	**18**
		E Lighting	To signal that the door is enabled	No signalling, lighting	Led defective, wiring interruption, tightening not suitable	**3**	Passengers could think the door is out of use but door is functioning	**2**	**6**
				Permanent signalling, lighting	Short circuit, external voltage	**3**	Passengers could think the door is in use but door is not functioning, passenger discomfort	**3**	**9**
			To signal that the door is not enabled	No signalling, lighting	Short circuit, external voltage	**3**	Passengers could think the door is in use but door is not functioning, passenger discomfort	**3**	**9**

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Table 5 continued

No	Item	Sub-item	Function	Failure modes	Potential causes	O	Potential effects	S	R
				Permanent signalling, lighting	Led defective, wiring interruption, tightening not suitable	3	Passengers could think the door is out of use but the door is functioning	2	6
	F	Fixed step	To support entrance for passengers	Shears off/fixing does not hold	Material failure, damaged fixing	1	Passenger could fall to the track, passenger injury	9	9

Table 6 Current maintenance programme for the passenger door system

Task	Task description	Mileage
Current maintenance programme		
1	Passenger bodyside doors—unit functional check (via HMI)	16,000
2	Bodyside doors—door functional check	16,000
3	Automatic passenger counting system—sensor covers clean and inspect	38,800
4	Bodyside doors—examine	51,800
5	Automatic passenger counting system—detection of height of sensor check.	80,000
6	Bodyside doors—minor lubrication	160,000
7	Bodyside doors—check of painting	160,000
8	Bodyside doors—major lubrication	320,000
9	Bodyside doors—visual inspection	320,000
10	Bodyside doors—check of clearance and replacement of energy chains	1,553,500
11	Bodyside doors—replacement of rubber spacer and NOVRAM	1,553,500

By implementing such a PM programme, the reliability of the door system will undoubtedly increase as the majority of failures can very likely be detected and rectified with certain mileage-based maintenance tasks at the periodicities given. However, a further study will be required to assess the performance of the proposed maintenance programme in terms of system availability, service reliability and safety and cost of IMR.

5 Conclusions and Future Work

In the current study, a failure mode, effects and criticality analysis (FMECA)-based approach was presented to identify, analyse and evaluate the potential risks associated with unexpected failure of rolling stock components. The criticality level of a rolling stock failure is calculated by multiplying the likelihood of occurrence of the failure mode (O) and the severity of damage caused by the failure (S), each being rated with a number from 1 to 10 (1 = lowest, 10 = highest). The failure modes according to the level of their criticality were categorised into five classes, namely very low, low, medium, high and very high critical. The most critical failure modes in the system with respect to both reliability and economic criteria were identified and possible methods for mitigation were discussed.

The analysis model was applied to the passenger door unit of a fleet of 38 Class 380 trains operating on Scotland's railway network. The data required for the analysis were collected from the literature, the company's

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Table 7 Proposed PM programme for the passenger door system

Task	Task description	Mileage
Proposed PM programme		
1	Bodyside doors—condition monitoring of door signalling via remote diagnostics to include data for all doors, proactive tasks	~533
2	Bodyside doors—Test door functionality from HMI and also locally	16,000
3	Bodyside doors—general visual inspection of the door running gear for loose components	32,000
4	Bodyside doors—inspect locking roller, synchronisation cable, guide roller and guide plate	48,000
5	Bodyside doors—test functionality of light barrier system	48,000
6	Bodyside doors—test door functionality guard operating panel	64,000
7	Bodyside doors—inspect the spindle and nut for security	64,000
8	Bodyside doors—inspect, clean and lubricate locking shift, locking roller, guide roller and guide plate	160,000
9	Bodyside doors condition monitoring of energy chain	160,000
10	Bodyside doors—functional test	200,000
11	Bodyside doors—major lubrication	320,000
12	Bodyside doors—visual inspection	320,000
13	Passenger bodyside doors—check of clearance and replacement of energy chains	1,553,500
14	Bodyside doors—replacement of rubber spacer and NOVRAM	1,553,500

maintenance management software system called EQUINOX, the UK's railway performance management software DATASYS BUGLE and the UK's train movements monitoring system called TRUST. The five why's technique was used to identify the potential failure modes of door unit components and their root causes, including the defects in relation to pushbuttons, door control unit (DCU), mechanical failures, light barrier, door drive, guard operating panel (GOP), limit switches, loose plugs, obstructions, door roller and lubrication. The results of the risk evaluation showed that the nine failure modes (12 % of the total number of failure modes identified) are "high critical" to door system functionality. The results of this study were used not only for assessing the performance of current maintenance practices, but also to plan a cost-effective preventive maintenance (PM) programme for different components of rolling stock. To avoid the recurrence of the failure modes, a new mileage-based preventive maintenance (PM) programme including 14 tasks was proposed.

There is a wide scope for future research in the area of risk analysis in relation to railway rolling stock failures. Some of the possible extensions of the present work are as follows:

a. proposition of a multiple criteria FMECA approach for risk evaluation of different rolling stock components;
b. evaluation of the cost effectiveness of PM programmes for rolling stock with respect to risk evaluations (see [25]);
c. development of a more quantitative approach to characterise the likelihood that a rolling stock failure may occur and the impact of likely consequences.

Acknowledgments The authors gratefully acknowledge the support provided by the Scottish train operating company during field visits and data collection.

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