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Towards implementing condition based maintenance policy for rolling stock critical system

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Abstract

Rolling stock critical system failures require condition based maintenance (CBM) policy to optimise maintenance tasks and hence improve reliability and availability of service operation. In this paper, the implementation of CBM analysis for Class 158 Diesel Multiple Unit (DMU) train door system is presented. The condition monitoring of the door system information collected falls into the category of partially observable systems. Condition monitoring trial results of the doors is presented to show specific signs of door deterioration and repeating failures. A stochastic signal pulse model is proposed that could utilize CBM information to schedule optimum cost effective maintenance strategy.

1 INTRODUCTION

1.1 Rolling stock background

Condition based maintenance of rolling stock is a major task in the railway industry because an in-service failure could lead to delays and passenger dissatisfaction. Moreover, in-service failure increase maintenance cost and hence has a knock on effect on the overall availability and reliability performance of train fleets. The 158 DMU fleet is selected as a result of the current poor performance that is mainly attributed to the doors failures. Consequently safety and reliability is of paramount importance to the company. This paper focuses on the door systems of the Class 158 DMU units train fleet. There are 48 Class of 158 DMU trains that consist of mainly 2 and 3 car vehicles. Each vehicle has 4 doors and each door system consists of several functionally dependent components. The doors are frequently monitored at discrete time points. In this paper we attempt to optimize the maintenance of the door system using condition based maintenance given that they have been operating for certain number of months. The nature of the door system component design weaknesses is not revealed in this paper because of confidentiality.

The reliability and availability performance of rolling stock fleet is supported by a good preventive maintenance plan. However, a condition based maintenance programme in expected to improve fleet reliability to an acceptable level. The train fleet considered in this paper is fitted with On-line Train Data Recorder (OTDR). The OTDR is expected to meet the varied requirements of systematic safety monitoring procedures, and can also be used for wider deployment of condition determined maintenance policies. An extensive review of diagnostics and prognostics analysis implementing condition based maintenance models is discussed in (1). Condition-based maintenance (CBM) can be used to monitor asset health regularly in order to maximize reliability and availability and also in determining necessary maintenance at the right time. A framework of condition based maintenance approach on rotating mechanical systems is discussed in (2). A case study on the condition monitoring of railway equipment train rotary door operator is presented in (3). Critical appraisal of other condition monitoring techniques and its application in the railway industry is discussed further in Section 3.

1.2 Fleet performance data

The train operating companies in the United Kingdom are required to provide performance data to the Rail Delivery Group (RDG) to show progress regarding their Public Performance Measure (PPM). The PPM is a combined measure of the reliability and punctuality of trains throughout the TOC's network. A train is defined as having a PPM pass if it arrives at its destination within 5 minutes of the scheduled arrival – i.e. 'on time' and is not cancelled or partially cancelled.

The DMU fleet performance is calculated by analysing the fleet in-service failures. Trains that fail in-service can have different degree of disruption to services for example, minutes delayed, part cancellation of a service or full cancellation of a service of any train. For example if a single unit of the Class 158 vehicle has a door fault and is delayed for 7 minutes before leaving the station. It also causes two other trains to be delayed by 5 and 10 minutes. Very quickly a 7 minutes delay in one station can accumulate into a 100 minutes delay and subsequent cancellation of service. The fines attributed to delays and cancellation can increase very rapidly over a short space of time.

The class 158 door systems are the second poorest performing system with about 235 incidents related to the door faults recorded in the last 13 periods between 2015 and 2016. The graph in Figure 1 shows the door incident breakdown and the defective type code "O" on the graph relate to the doors while the other codes are attributed to other systems.
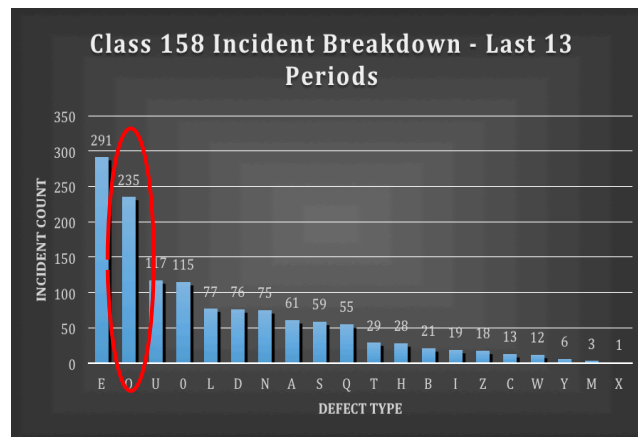

Figure 1 Door incident breakdown

As part of the Class 158 DMU fleet performance improvement plan, the door faults are being reviewed to address root cause and hence identify potential failure modes. A comprehensive study using the reliability centred maintenance approach of the class 158 doors to identify critical classes of failure modes is presented in (4). Reliability analysis of rolling stock failure patterns is discussed in (5). From some of the literature consulted the preventive maintenance is considered to be one of the most difficult task to model in the field of maintetance and sometimes the result on preventive maintenance actions is somewhat cost effective but does not classify causes of breakdown incidents. To this aim condition monitoring on the door as critical system is envisaged and the study conducted is presented in this paper.

2   OVERVIEW OF DOOR SYSTEM AND COMPONENTS

2.1   Door system

The class 158 DMU train is fitted with four external bi-parting swing plug doors per vehicle for both passenger and crew access. The train door example is presented in the picture in Figure 2 below. The doors are electrically controlled and pneumatically operated.

Figure 2. 158 Door system

When a passenger presses the illuminated door open button, the pneumatic system operates to allow air in to the torque cylinder. This unlocks the door over centre locking mechanism and causes the torque cylinder to rotate. The torque cylinder operates linkages attached to each door leaf opening the door. When a passenger presses the illuminated close button or the conductor presses the closed button on the door control panel the

torque cylinder operates to close the open door. The door closes and is mechanically locked over centre as show in the control panel in Figure 3.
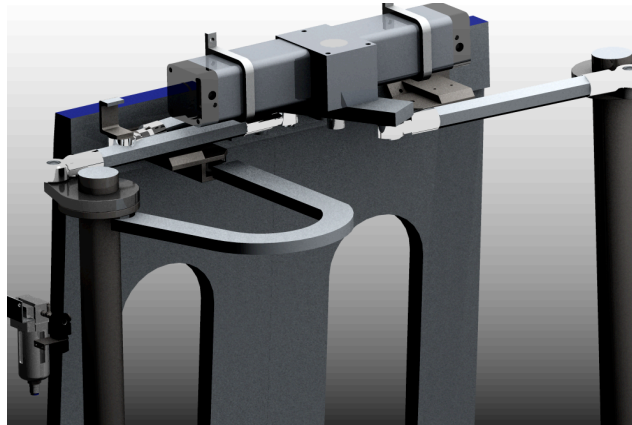

Figure 3 Door control panel

2.2 Maintenance of door system

Maintenance conducted on the door system is referred to an exam. Exam A and B are conducted on the trains. Exam A is a shorter exam than the Exam B and which consist of conducting regular maintenance on safety critical systems every 10k miles. For example door components are checked for functionality during an A exam to ensure that the passenger doors are functioning properly. The test conducted on doors every 10k miles presents a chance to conduct opportunistic maintenance. Bedford and Alkali (6) discuss the competing risk incorporating opportunistic maintenance models. A delay time model is proposed in an attempt to model preventive maintenance policy of train doors presented in (7). A failure mode, effects and criticality analysis of rolling stock critical systems is conducted in (8) and the outcome is used to further proposed a generic framework using risk-based maintenance. The difficulty of optimising the preventive maintenance of the doors is beneficial in economic terms however it is at an expense of reduced fleet availability for service operations. To this aim condition based maintenance is envisaged as a way forward towards improving the maintenance actions and hence improve the reliability, and availability of rolling stock the door system. The design and evaluation of remote measurement for the online monitoring of railway vibration signals is discussed and analysis of vibrations results is presented in (9). The paper presented in (9) also provide a very good framework for utilizing on-line condition monitoring of railway assets.

3 CONDITION BASED MAINTENANCE

3.1 Condition monitoring

Condition-based maintenance (CBM) is a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring (1). It consists of three main steps: data acquisition, data processing and maintenance decision-making. Condition monitoring data are very versatile. Reliability has always been an important aspect of assessing equipment design and maintenance plays a key role in ensuring an efficient way to assure satisfactory level of reliability. Some relevant studies using condition monitoring techniques are investigated for example a disgnosis of fault test results from a new class of closed-loop electric train door in (10), were used to develop a mathematical model that could form the basis of a fast-response condition monitoring system. The use of sensor in vital in the use condition monitoring of systems. A study of train sensor and reporting systems is essential in condition monitoring to support the decision maker on which maintenance policy to consider. A pattern recognition approach for the prediction of infrequent target events in floating train data sequences within a preventive maintenance framework is discussed in (11). The paper in (12) present a research conducted on how to improve the reliability of single-throw equipment used in railway signalling processes, rolling stock as well as power systems. The maintenance strategy of commercial trains is supported with both positioning and communication systems as well as onboard intelligent sensors monitoring various subsystems all over the train fleet, and thus providing real-time flow of information that is transferred to a centralized data servers via wireless technology is discussed in (13). Furthermore, the paper in (14) present the analysis and a case study using condition monitoring technique and its application in the railway industry.

Condition monitoring in the railway industry is not new however its application on critical systems is somewhat scarce. Other railway critical systems that condition monitoring have been applied to such as axle and bearing units is studied (15) and (16) respectively. A fault detection method for railway infrastructure point systems is

discussed in (17). A potential improvement of in-service inspection of wheel set using fatigue analysis is discussed in (18). A new method on condition monitoring of railway level crossing is presented also presented in (19).

3.2   Data acquisition

The Class 158 trains considerd in this paper are fitted with data acquisition system called the Nexala System. The system is compatible with the OTDR and can be used to analyse data approximately four seconds after being transmitted from the unit. The data is then analysed further to identify faults or warnings. Warnings flag up possible future problems in the form of signal pulse. This is processed immediately information is received and flagged up to the designated user or via email. Currently the vehicle transmits recording of driver actions and safety systems rather than the performance of the vehicle. The purpose of some of these channels is to allow for greater monitoring of the door systems. The following systems monitored are; the Door Key Switch "On" for doors A, B, C, & D, and the Passenger Door "Closed" for doors A, B, C & D.

   The Door Key Switch (DKS) and the Door Interlock Switch (DIS) are non-intrusive systems and somewhat contribute to technical incident resulting to delays in-service. The technical incidents in Table 1 below give an overview of top 3 failure modes by number of technical incidents related to the DKS and DIS system.

Table 1. Top 3 Failure modes technical incidents

Year	Failure model 1	Failure mode 2	Failure mode 3
2012	DKS defective	DIS adjusted	DIS defective
2013	DKS defective	DIS adjusted	DIS defective
2014	DIS adjusted	DIS adjusted	DIS short circuit

Maintenance is conducted to capture the top 3 failure modes every 7k miles in 2012 and 2013 respectively and in 2014 maintenance is conducted at 10k miles. The percentage of incidents and delays caused by the top 3 failure modes is presented in Table 2

Table 2. Top 3 % technical incidents & delays

Year	Maintenance	% of incidents	% of delays
2012	7k miles	66%	75%
2013	7k miles	43%	35%
2014	10k miles	38%	16%

   Notice from Table 2 above that the percentage technical incidents and delays caused by the DIS and DKS top 3 failure modes decreases as the maintenance intervals are extended over the years to 10k miles. However less maintenance is envisaged but has to be in compliance with railway safety standards procedures. To this aim the condition based maintenance pave a way as a good rationale for investigating the DKS and DIS that is addressed in this paper.

3.3   Condition monitoring trial results

Condition monitoring trial is conducted on one of the Class 158 (738) units. The trial incidents recorded show the most common causes of incidents attributed to the door DKS and DIS systems. The door slow to close is determined when the time taken to close the door is more than 8 seconds over the centre after pressing the door close button on the DKS Panel. Once the door close command is initiated the door release trigger and closes the Left Hand Side (LHS) or Right Hand Side (RHS). A "pulse" signal and the hustler alarm sound for 3 seconds before the doors start to close. It takes about 4 to 4.5 seconds for the door to close. For example if the door setting is calibrated with an additional 0.5 seconds it will flag many issues in relation to accuracy of timing.

Figure 4 indicates that the number of slow to close incidents on the door C is as high as 32 and this is due to the accuracy in the settings. However, after the rule refinement in the setting as shown in Figure 5, it highlights that the number is reduced to 2 which n principle is a 93.75% decrease in false reports.
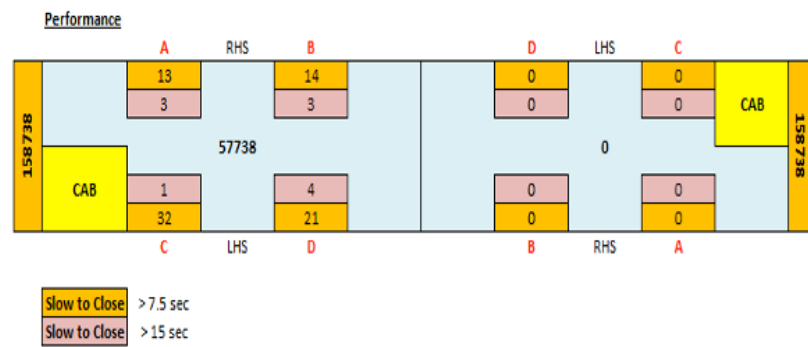

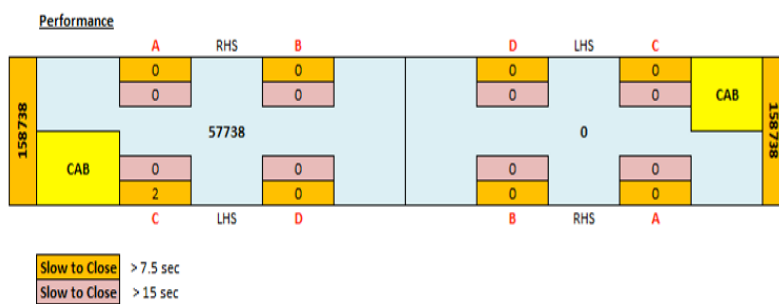**Figure 4. Slow to close incidents**

Figure 5. Slow to close incidents

The graph in Figure 6 highlights the new "slow to close", which identify performance issues in-service. Therefore, specific doors showing signs of deterioration and repeat failures (C door) can be recalled for performance improvements. It would be ideal to confirm the door C as being slow to close at the next maintenance interval.
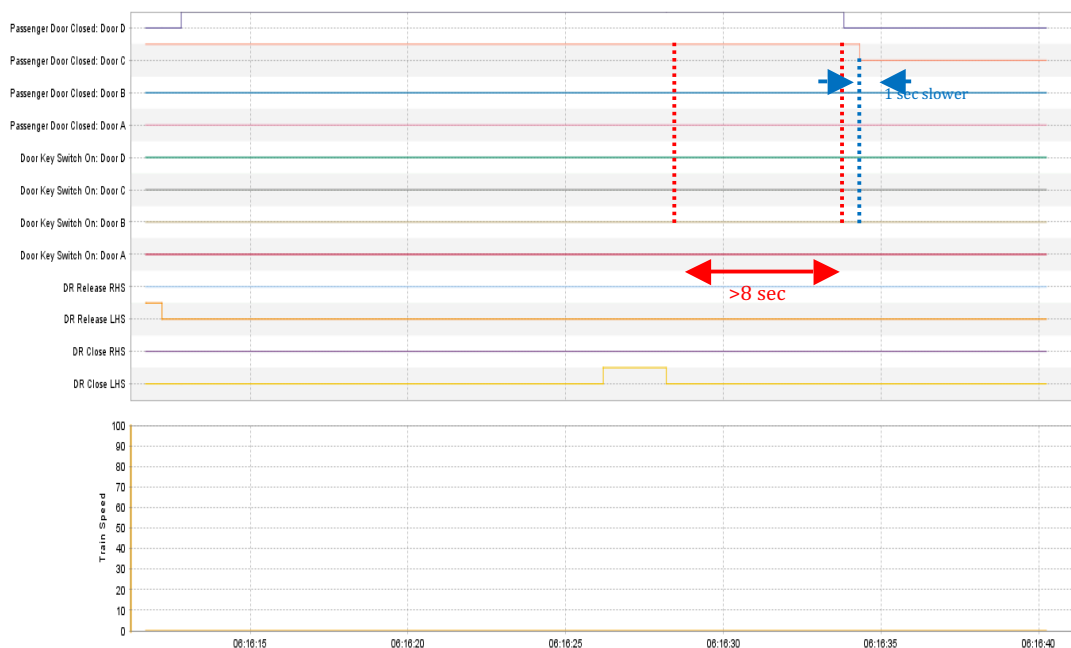

Figure 6. C door slow to close incident

From the trial conducted it is evident that there is certainly a defect associated with door C however the question is what is the cause of slow to close. The condition monitoring trial on the class 158 doors has given us an insight and the capability to flag up potential failures as a form of a "signal pulse". "Signal Pulse" monitors if the sensor signal from the DKS or DIS is active for less than a second (0ms – 1000ms). This identifies if there are any intermittent failures during service, which do not get identified during regular maintenance. The graph in Figure 7 indicate an intermittent failure on DKS door C.
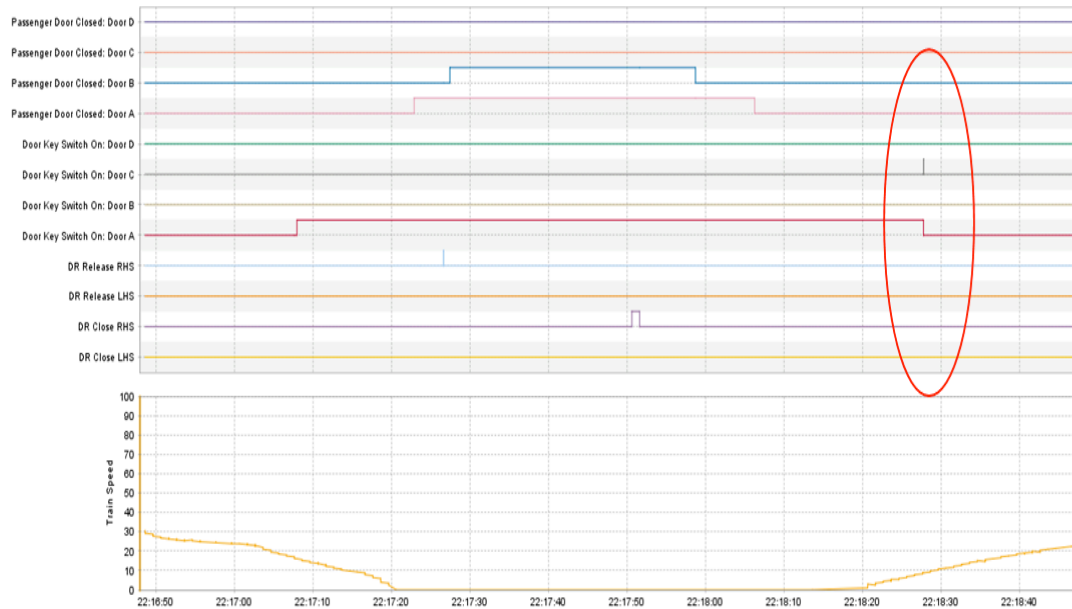

Figure 7. DKS door C signal pulse incident

Therefore, the signal pulse detected in Figure 7 give a clear indication of an intermittent failure. The condition monitoring trial has highlighted an intermittent failure with DKS door C previously (Figure 6). Therefore, this new readings (Figure 7) suggest that there is an underlying cause for the pulse signals that have not been corrected. Therefore, an OTMR download must be taken to confirm both recent intermittent failures and corrective action must be taken to prevent repeat failures of DKS door C signal recurring. A signal pulse occur randomly during monitoring and in this paper we assume that signal events to be stochastic. To this aim an attempt is made to model the intermittent failures using stochastic point process model.

4   STOCHASTIC PROCESSES

Stochastic processes are ways of quantifying the dynamic relationship of sequences of random events (20). A stochastic model predicts a set of possible outcomes weighted by their likelihood and probabilities. The models play an important role in elucidating many areas of natural applications. Stochastic point processes have been applied to repairable systems. They are mathematical models characterized by highly localized events distributed randomly in a continuum. The continuum is time and the highly localized events are failures, which are assumed to occur at instants within the continuum (21). The entire technique developed for point process models is potentially applicable to systems' failure data. The condition monitoring data presented earlier depicting signal pulse as intermittent failures is used and an attempt is made to predict the distribution of time to failure of the door components.

4.1   Stochastic Point process

   A stochastic point process represents the successive arrival and inter-arrival times of system failure, under the assumption that a system is operated whenever possible and that repair times are negligible. The pattern of failures necessarily develops in calendar time. For example the annual railway calendar in Scotland is split into 13 four-week periods as mentioned earlier in the Section 1.2. If a train is taken out of service and no repair is considered, the exact connection to calendar time disappears but the successive failures are still calendar time ordered (22).

4.2 Stochastic signal pulse model

The stochastic signal pulse model assumes that each pulse given is related to the actual door lifetime, but the model does not explicitly model the way in which the pulse could be attributed. This model proposed is a new development and is the main contribution in this paper. The model explicitly assumes the maintenance decision maker knows some kind of information about the state of the door system. The model is somewhat similar to the signal opportunity model in (6). The signal pulse model also has some of the features of the delay-time model discussed in (23), and also similar to the degradation model but differs in some important respects.

These signals pulse occur randomly but may be observed by the decision maker using condition monitoring tool and the failure mode identified could attributed to any of the top 3 failure modes associated to the DKS and the DIS door components. The modelling of the signal pulses give an idea and some knowledge of the state of the door system, and hence that the masking of signal pulse data will be correlated to the actual intermittent failure times.

Let $T_1, T_2, T_3,...$ be the times to successive intermittent failures of the door system and let $S_i = T_i - T_{i-1}$ be the time representing the signal pulse between failure $i - 1$ and failure i. The T_i and S_i are random variables and we define t_i and s_i to be their corresponding realized values. If we define an increasing sequence of signal times $S_0 = 0, S_1, S_2,. . .$, which are assumed independent but not necessarily identically distributed, and define further a failure rate $\lambda(t)$, $t > 0$ for each period after the $i-1^{th}$ signal S_{i-1}. The Distribution of the intermittent failure time T is defined conditionally. The probability of the door systems surviving a signal i^{th} signal $T > S_i$ is equal

$$exp\left(-\int_{0}^{S_i-S_{i-1}} \lambda_i(t)\,dt\right) \quad (1)$$

In this model it is assumed that the decision maker is aware of the signal times and the failure rates, and has adopted a decision rule saying that the first signal pulse given off attributed by any of the doors which is correlated to the intermittent failures will be used. If we assume that the times between successive signal is constant with time. This implies that the times between successive signals follow an exponential distribution. The expression for the conditional distribution function in terms of the signals is given in Equation (2) as

$$F(t \mid S_1, S_2,...S_n) = 1 - exp\left[-t\sum_{j-1}^{j-1}\left(S_{j-1} - S_j\right)\lambda_j + \left(t - S_j\right)\lambda_j\right] \quad (2)$$

Where λ_i is the failure rate of the doors and S_j is the largest signal pulse time less than t. The model proposed here is a general class of models in (24) and also mentioned in (6).

5 CONCLUSIONS

The condition monitoring techniques considered in this paper and the series of example scenarios associated with the rolling stock door system is presented. The challenges associated to door performance and reliability improvement, and the effect it has on service operations are clearly highlighted. The condition monitoring trial result conducted on the door systems is presented. The outcome of the trial demonstrates a new development towards monitoring state of the critical components (DKS and DIS) of the door systems is addressed.

The stochastic signal pulse model with random exponential features is proposed and has been discussed in this paper. The data arising from monitoring the state of the door systems occur randomly and stochastic point processes is deemed appropriate to consider within the framework of the proposed signal pulse model. The model considers the way in which intermittent failure data is censored by preventive maintenance. The model is inspired by both a study of the practices in the railway industry. Simulation of the proposed signal pulse model to predict the time to failure of the door system is envisaged and the simulation work is still an on going and will be presented in future publications.

6 ACKNOWLEDGMENT

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