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Road and Rail Infrastructure V

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UNCERTAINTY AND RISK QUANTIFICATION IN RAILWAY MAINTENANCE MODELLING

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Abstract

The relatively long life cycle of railway infrastructure means that maintenance and renewal decisions significantly influence the total life cycle cost (LCC) associated with the infrastructure. A decision support tool such as life cycle costing assists infrastructure managers in making maintenance and renewal decisions. A shift from qualitative to quantitative decision making is possible using decision support tools and modelling approaches based on appropriate data. Most LCC maintenance models in the literature are deterministic in nature. However, there is inherent uncertainty present within the reliability and maintainability (R&M) parameters. The uncertainty within the R&M parameters can be characterised through appropriate statistical distributions or using bootstrapping in conjunction with available data. A maintenance modelling approach based on stochastic methods and Monte Carlo simulation is presented in this paper with specific attention to a model developed for the rail component. The proposed model allows quantification of inherent uncertainty within the calculated LCC which is coupled to the uncertainty within the input R&M parameters. This modelling approach is flexible in nature and supports the use of large input data sets, capturing variability within the real-world situation of maintenance management. The flexibility of the modelling approach is demonstrated using an example which incorporates risk to assist an infrastructure manager in deciding whether to use flash butt or alumino-thermic welding during rail maintenance.

Keywords: Monte Carlo simulation, life cycle cost, uncertainty, maintenance modelling, rail

1 Introduction

The operational demands on railway infrastructure are increasing through increasing axle loads and an aimed reduction in maintenance delays to accommodate higher traffic throughput. Concurrently, maintenance costs are rising and budget restrictions are tightening [1]. This is particularly true for heavy haul rail freight operations. The maintenance component of the total life cycle cost (LCC) is significant due to the long life span of railway infrastructure [2, 3]. Therefore, an opportunity exists to minimise the LCC of owning and operating railway infrastructure through minimising of the maintenance cost over its service life. The relative contribution of maintenance to the total life cycle cost of railway infrastructure is illustrated qualitatively in Fig. 1.

It is arguable that the rail of a railway track is the most critical component within the complex system comprising a complete railway infrastructure set [4]. The rail contains no redundancy and therefore maintenance of the rail is critical. Maintenance models for the rail are abundant in the literature [5-8]. Of the models highlighted, the majority are derived using closed-form solutions which lend themselves to simple optimisation. However, the limitation associated with closed-form modelling approaches is that they do not explicitly account for the inherent uncertainty within the reliability and maintainability (R&M) parameters on which the models

are based. The uncertainty within the R&M parameters used in maintenance models was directly addressed by Patra et al. [8]. There is a need to quantify the uncertainty within the R&M parameters used in modelling approaches and to assess its influence on the uncertainty in the final calculated LCC.
This paper proposes a stochastic maintenance modelling approach for the rail incorporating Monte Carlo simulation to quantify the uncertainty in the calculated LCC as a result of the uncertainty in the R&M parameters. Particular focus is given to the application of this approach in aiding with the decision of whether alumino-thermic welds (ATWs) or flash butt welds (FBWs) should be used for maintenance of the rail in order to reduce the total LCC.

2 Stochastic maintenance model

This section provides an overview of the maintenance model developed and used in this study. Only key points are highlighted within the modelling procedure and references [9] and [10] should be consulted for a detailed discussion. The maintenance model introduces uncertainty into the calculation of the LCC at three key points within the modelling procedure. These are:
- The arrival of fatigue defects within the welds and the rail itself.
- The time from when a defect forms to when a functional failure occurs.
- The detection of a defect in a weld or the rail during an inspection event.

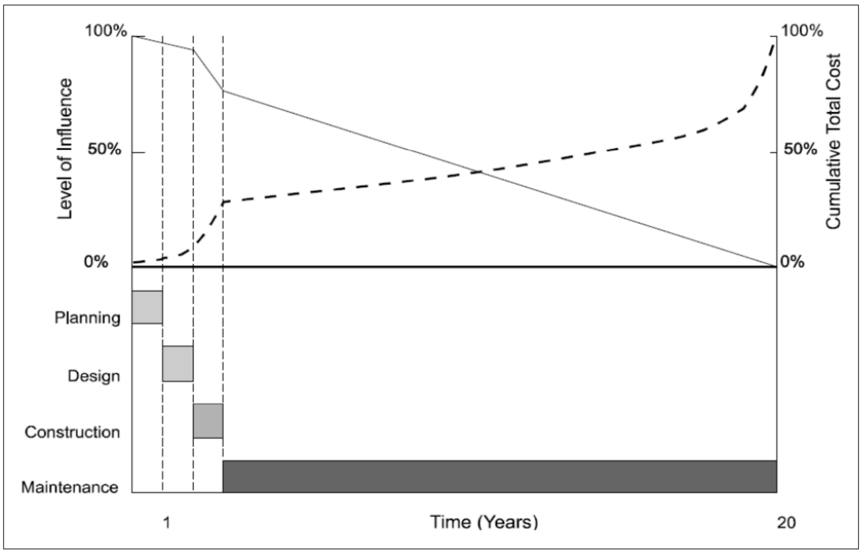

Figure 1 The relative contribution of maintenance costs to the total life cycle cost of railway infrastructure [2]

The arrival of rail defects in the model is described using the hazard rate function of a two-parameter Weibull distribution as the intensity function within a non-homogenous Poisson process and is discussed in Section 2.1. The time from when a defect forms until a functional failure occurs is termed the P-F Interval [11] and is described using an exponential distribution, assuming independent and identically distributed P-F interval lengths. Rail inspections are imperfect and the process is essentially a Binomial process. The probability of detecting a defect is specified for each rail defect type taking into account the specific inspection process used. Therefore, the probability of detection could be varied depending on whether modern ultrasonic and eddy current inspection technologies or visual inspection is used.

2.1 The hazard rate and categorising of defects

The arrival rate of rail fatigue defects is described using a hazard rate function [12], $\lambda(t)$ with respect to the tonnage borne by the rail, t. The hazard function is defined such that $\lambda(t) \cdot dt$ represents the probability that a defect will form within the rail in the time interval $(t; t + dt]$.

A two-parameter Weibull distribution is used to model the arrival of defects in this way [5, 13]. The hazard function for the two-parameter Weibull distribution is described by Eq. (1):

$$\lambda(t) = \frac{\alpha}{\beta^{\alpha}} t^{\alpha-1} \tag{1}$$

where α is the shape parameter and β the scale parameter with units of million gross tonnes (MGT). It should be noted that the arrival of a defect is defined as that state when a defect theoretically becomes detectable.

The hazard rate function is the intensity function within the non-homogenous Poisson process which describes the inter-arrival times of defects (or time-to-defect initiation). The cumulative density function (CDF) for the time-to-defect initiation t_d, given the above assumptions, is given by Eq. (2):

$$F(t_d) = 1 - e^{-\left(\frac{t_d}{\beta}\right)^{\alpha}} \tag{2}$$

Eq. (2) is used together with an inversion process and Monte Carlo simulation [14] to sample random variates for t_d during simulation of the virtual life cycles in the model.

Rail defects are divided into Category A and Category B defects for modelling purposes. This classification system is similar to the classification system proposed by Marais & Mistry [15]. Category A defects are defects related to the joining of the rail and only ATWs and FBWs are considered in this study. Category B defects are related to the overall quality of the rail, such as tache ovale and squat defects [16]. This distinction is important because the hazard rate for Category A defects is specified for a single weld whereas the hazard rate for Category B defects is specified per km of rail within the model. The model simulates one representative km of rail. The modelling procedure accounts for the increasing overall hazard rate of the system as welds are added to the system due to maintenance of both Category A and B defects. Perfect maintenance [17] was assumed in the model used for this study whereas minimal maintenance was assumed in [5] and [6] in order to provide a closed-form solution for the LCC equation. Due to the nature of the different welding processes, ATWs have a shorter service life than FBWs. This is evident in analyses of rail break statistics [15, 18]. However, larger, less mobile and more expensive equipment is required to conduct flash butt welding. The two main contributing factors to account for in deciding whether to use flash butt welding or alumino-thermic welding are thus the difference in weld integrity and the difference in maintenance cost. The service life of the welds is controlled by the shape parameter α and the scale parameter β of the Weibull distribution within the time-to-defect distribution given by Eq. (2).

A parametric analysis was conducted to quantify the influence of different $\alpha - \beta$ value pairs on the probability density function (PDF) and CDF of t_d for ATWs and FBWs. A single hazard rate function for ATWs and another for FBWs were used in [5]. However, this was expanded upon and the concept of a superimposed hazard rate function to represent both early defects and fatigue defects within ATWs was used in [6]. This was not done for FBWs as early defects in FBWs are less common. The α and β values used in [5] and [6] are shown in Table 1. A visual comparison of the PDF and CDF of t_d for the $\alpha - \beta$ value pairs given in Table 1 are shown in Fig. 2. Only the resultant functions are shown and not the constituents from which they are superimposed.

In order to simulate the longer service life (larger t_d) of FBWs as opposed to ATWs, one would intuitively expect that the CDF of t_d for ATWs should lie above the CDF for FBWs. This would then indicate that at any given value of t_d the probability of having that t_d or smaller would be greater for ATWs than for FBWs. Fig. 2(b) shows that the CDF used in [6] for ATWs lies well below the CDF for FBWs. This would suggest a longer service life for ATWs in general and is not representative of statistics as given in [15] and [18]. The single hazard rate function used for ATWs in [5] is an improvement to that used in [6]. However, for $t_d > 260$ MGT the CDF for FBWs still lies above the CDF of ATWs.

This result led to the proposal of a new superimposed hazard rate function for this study as shown in Table 1 and Fig. 2. Only the α and β parameters of the hazard rate function for fatigue defects were changed. It can be seen that the ATW CDF with the proposed parameters lies above the FBW CDF. The behaviour at $t_d > 800$ MGT was not investigated and is not considered significant as this area of the PDF contains little probability density which can be seen at $t_d \approx 800$ MGT in Fig. 2(a). The new proposed hazard rate function parameters for ATW fatigue defects still displays a peak in probability at $t_d \approx 0$ MGT which emulates early failures of ATWs (this peak is the short-dashed line which appears parallel to the vertical axis in Fig. 2(a); hidden due to scaling). Thus, overall it displays behaviour which is more consistent from an intuitive viewpoint than that proposed in [6].

Table 1 Hazard rate function parameters used in [5] and [6] to characterise ATWs and FBWs

Weld Type	Model	Early defects		Fatigue defects	
		α	β	α	β
ATWs	[5]	–	–	1.01	315.8
ATWs	[6]	0.18	2.1×10^{14}	1.10	1737.0
ATWs	Proposed	0.18	2.1×10^{14}	1.70	200.0
FBWs	[5], [6]	–	–	2.00	286.6

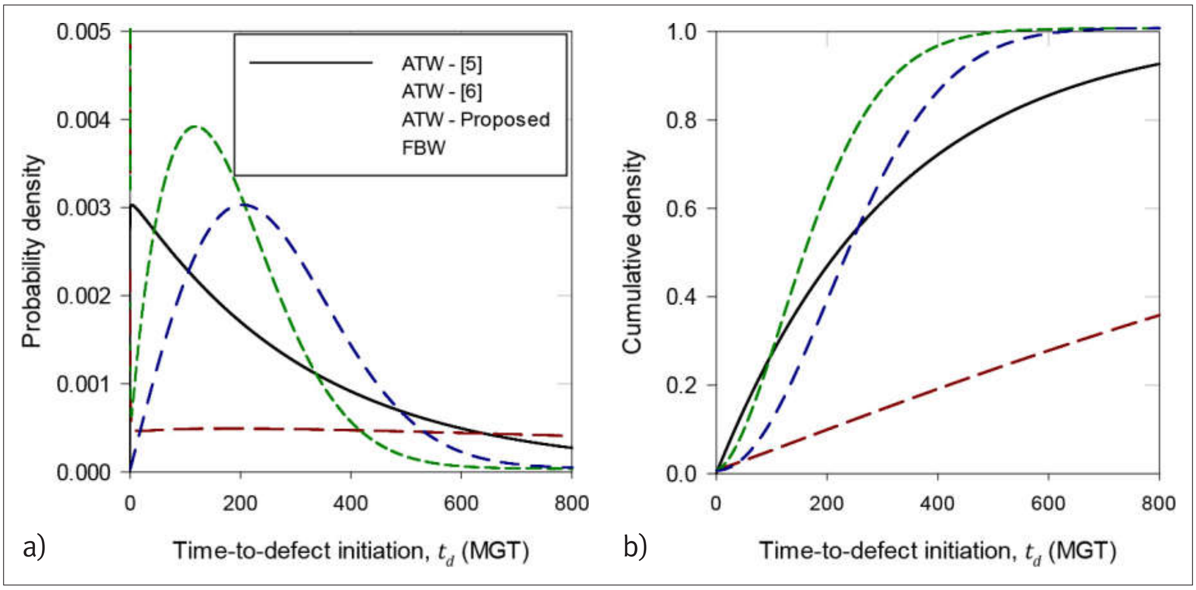

Figure 2 Comparison of different α – β pairs on a) the PDF and b) the CDF of the time-to-defect t_d for ATWs

3 Alumino-thermic welding versus flash butt welding

The output of the stochastic maintenance modelling process in terms of normalised life cycle cost c_{LCC} and renewal tonnage T_R for a given set of input R&M parameters can be represented in three-dimensional space using a bivariate histogram as shown in Fig. 3(a). The input parameters used for the results shown in Fig. 3(a) can be found in [10]. The same input parameters were used for this study excluding the hazard rate function for ATWs which are as shown in Table 1. Also, shown in Fig. 3(a) are fitted lognormal distributions for fixed values of T_R. Numerous distributions were tested and the lognormal distribution provided the best fit to the distribution of c_{LCC} at fixed values of T_R [10].

Simulations were run with the new hazard rate functions and for different ratios of flash butt welding to alumino-thermic welding cost c_{FBW}/c_{ATW}. A fixed reference alumino-thermic welding cost of R16 000 (South African Rand) was used. Fig. 3(b) shows the distribution of c_{LCC} at a value of T_R = 400 MGT with c_{FBW}/c_{ATW} = 1.0 for an analysis which used ATWs for maintenance with a hazard function as used in [5] and for an analysis which used FBWs for maintenance. The distribution of the difference between the LCC for the ATW case and the FBW case $c_{LCC_{ATW}} - c_{LCC_{FBW}}$ is also shown in Fig. 3(b). The probability $P[c_{LCC_{ATW}} - c_{LCC_{FBW}} > 0]$ represents the probability that a lower LCC can be achieved if FBWs are used for maintenance for a fixed value of c_{FBW}/c_{ATW} for the given set of R&M parameters.

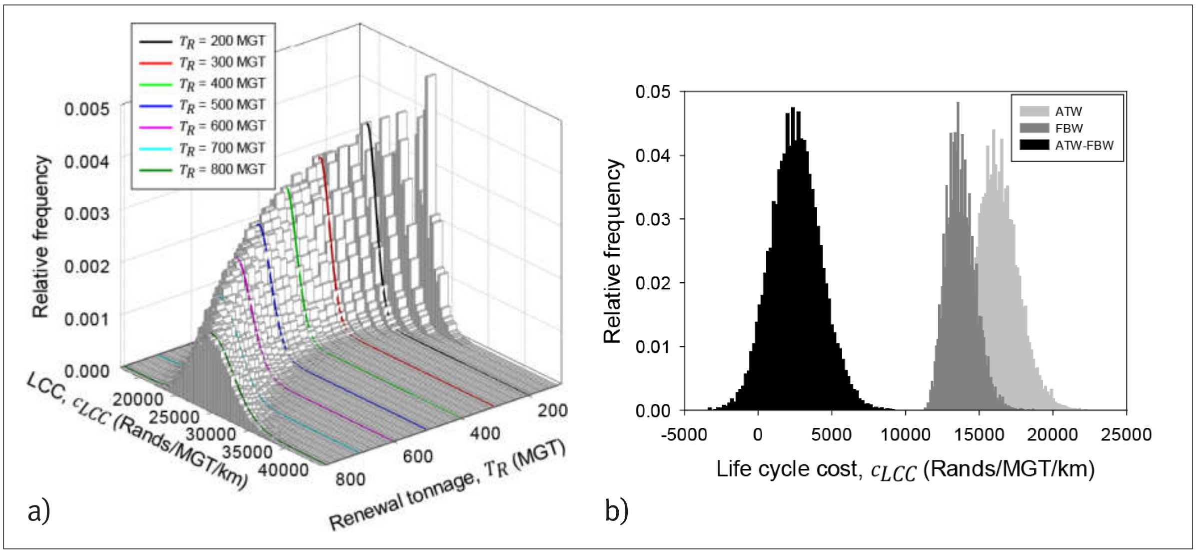

Figure 3 a) Bivariate histogram of c_{LCC} versus T_R; b) relative frequency plot of $c_{LCC_{ATW}}$, $c_{LCC_{FBW}}$ and their difference $c_{LCC_{ATW}} - c_{LCC_{FBW}}$

The process illustrated in Fig. 3(b) is repeated for all values of T_R modelled and at different ratios c_{FBW}/c_{ATW} representing different flash butt welding costs. This is also done for two ATW hazard rate functions namely that used in [5] and that proposed in this study (see Table 1). The result of this procedure is shown in Fig. 4 and illustrates how different combinations of the FBW and ATW hazard rate functions influence the shape of the probability curve at different cost ratios. The unfilled markers in the figure represent the results using an ATW hazard function modelled as in [5] and the filled markers are the results using an ATW hazard function modelled as proposed in this study. Fig. 4 shows that the probability

$$P[c_{LCC_{ATW}} - c_{LCC_{FBW}} > 0]$$

is strongly related to hazard rate functions chosen to represent ATW and FBW behaviour. For the hazard rate modelled after [5], it is clear that there is a peak in the probability at T_R = 400 MGT after which the probability curve decreases. This is indicative that the hazard rates used in [5] do not overall provide larger t_d values for FBWs than ATWs. The proposed hazard rate for which the ATW CDF lies above the FBW CDF (Fig. 2) illustrates the intuitive behaviour expected, in which the LCC benefits of using FBWs for maintenance manifest at large T_R values.

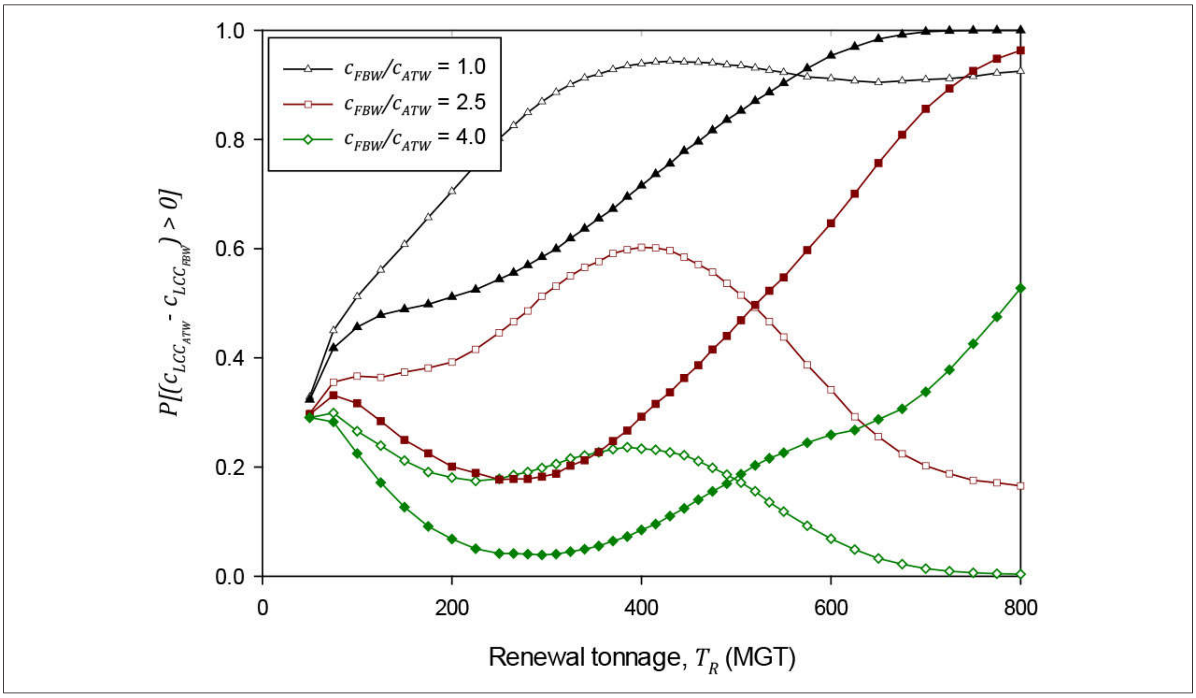

Figure 4 Probability curves for different combinations of ATW and FBW hazard rate functions at diff. cost ratios

4 Conclusions and recommendations

A study of the hazard rate functions used to model the time-to-defect t_d for ATWs and FBWs was conducted. The parameters from two previous studies [5, 6] were initially considered. The CDF of t_d for ATWs should lie above the CDF for FBWs based on the fact that FBWs have a longer expected service life than ATWs. The hazard rate functions considered in the literature did not model this behaviour appropriately and hence new parameters were suggested for the hazard rate function for ATWs in order to model this behaviour.

The hazard rate function from [5] as well as the newly proposed hazard rate function were used to conduct an analysis to test whether FBWs or ATWs should be used from a LCC point of view. This analysis showed that if the CDF of t_d was modelled to be representative of the longer service life of FBWs, then the benefit of using FBWs for maintenance would manifest at larger renewal tonnages T_R. Infrastructure managers can quantity their risk in shifting over to an alternative form of maintenance and make the correct decision, taking into account the risk profile they deem appropriate for their situation.

The α and β parameters for the hazard rate function for ATWs were chosen based on a combination of engineering judgement and previous studies from the literature. In reality, infrastructure managers may use data obtained from their network, or laboratory tests on specific welds to provide a suitable population of failure data from which the bootstrap method may be applied. This will provide an accurate input distribution representing the uncertainty within the R&M parameters.

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