Reschedule or not? Use of benefit-cost indicator for railway track inspection

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ABSTRACT: Effective planning of railway track inspection utilises characteristics of a track condition degradation model. When a statistical approach is adopted for track degradation modelling, prior knowledge about uncertainty of model parameters normally receives an update when new inspection data arrive. The model updating can suggest a new inspection schedule and/or with additional inspection(s) in some parts of the existing schedule. However, the suggestions to improve inspection schedule effectiveness might not work unless the rescheduling plan can be economically justified (i.e. the benefit-cost ratio remains greater than 1). Thus, this study proposes an indicator, this is, signifying whether a plan to reschedule the affected part of the inspection schedule should be carried out or not. To achieve the goal of this study, we modify the benefit-cost model of track preventive maintenance. As a result, the indicator which takes the probability of defect detection and an absolute deviation between the likelihood of a sudden shift and the ratio of two maintenance costs into account is formulated. Two disruption scenarios of track inspection schedule are considered in this study to demonstrate how the proposed indicator can be utilised in practice.

1 INTRODUCTION

Performing maintenance to railway infrastructure, which comprises signalling system, bridges, tunnels, drainage and track, can be quite tricky due to evidence of budget overspending as well as huge compensation paid for track possessions, delays and cancellations in recent financial reports (Office of Rail and Road 2015; Office of Rail and Road 2016). Both situations send a clear signal for innovations, i.e. deep investigation of weaknesses in the current practice of railway maintenance planning, particularly with regard to inspection delivery, which is one of the key areas in designing an effective maintenance plan (Jimenez et al. 2011).

In general, for railway track maintenance, presenting an appropriate inspection strategy is one of the prerequisites for overall track maintenance costs minimization, which positively affects the net benefit of long-term infrastructure investment (Stenström et al. 2016; Arasteh khouy et al. 2016). Apart from inspection frequency setting, an interval selection between two consecutive inspections has been determined as a crucial element in the cost evaluation. Casually defined inspection intervals without careful consideration, including simply following a specified or recommended standard without in-depth understanding about internal and external uncertainties, may result in either loss of efficiency in inspection or less benefit from maintenance. In response to the requirement to maximize the corresponding net benefit, many optimization models have been proposed, in which mostly are subject to periodic inspection style (regime) (Guo et al. 2015; Liu et al. 2014).

Periodic inspection is basically performed for a repairable system e.g. railway tracks to verify its safety and performance by detecting potential and hidden failures. It is relatively simple to implement and probably is the most common maintenance policy applied in practice to repairable systems.

Despite general advantages of having a prescribed schedule, the inspection sequences and resources allocation are designed under uncertainty. In their study, (Zhang & Mahadevan 2000) explained the different types of uncertainties that arise in modelling non-destructive inspections, which in principle demands parallel and/or hierarchical complex analysis due to a number of constraints, such as lack of quality data, model characteristics and design, knowledge–interpretation clash and inadequate information. Comprehensive discussion with regard to this issue can be found in (Brugnach et al. 2008). Acknowledging that these difficulties cannot be completely managed at the design phase, reschedule strategies have been developed (Albrecht et al. 2013).

Reschedule remaining inspection decisions from the original schedule might improve the planned maintenance plan to some extent. This is achieved either by transforming the existing schedule from periodic to non-periodic style or adding few additional inspections. Prior to decision making, a benefit-cost analysis (BCA) of track inspection reschedule must be presented. The BCA is a common practice in every department in any business sector to project company cash flow in future flow when an investment in new or improving the current product (or service) is proposed. To execute the process analysis successfully, expected benefits from and costs applied to the proposal should be properly formulated before the identification of the driving factors that influence the benefit–cost trade-off are carried out. Thus, this paper proposes an extension of benefit-cost analysis to achieve the abovementioned objectives with respect to the condition-based railway track maintenance.

2 COST FACTOR IN ASSET MAINTENANCE

In respect to infrastructure/asset ownership that looks for long-term dividend/return, a life cycle cost (LCC) approach has been widely applied in order to compute, analyse and compare the total cost that appears throughout the whole lifespan of the infrastructure to support an investment decision (Thoft-Christensen 2012). LCC generally covers the cost of acquisition, design and development, production, operation and support and disposal. In terms of inspection and maintenance, impacts of the proposed design and decisions, in the long run, directly appear in the operation and support cost, as illustrated in a cost distribution diagram (Obrenovic et al. 2006; Office of the Secretary of Defense 2014), see Figure 1. In further support of these claims, several researchers have pointed out that capacity, substance and quality of railway tracks are major parameters that should be stressed on when evaluating track maintenance cost over the remaining lifetime (Zoeteman 2001; Setsobhonkul et al. 2017). There is no single precise definition of railway capacity, but this parameter relates to traffic volume, train path, supply and demand, stability and heterogeneity (Burkolter 2005). Meanwhile, the amount of useful lifetime and quality of the track's components refer to the second and third parameters, respectively. Nevertheless, interdependence among these parameters is observable in the maintenance component of the LCC model, which can be systematically drawn from a cost breakdown structure.

The cost breakdown structure is a tool, at the analysis stage of LCC process for identifying all relevant activities that consume the organizational resources or the so-called 'cost elements' with respect to each cost category, e.g. maintenance costs. A precise definition and formulation are important to avoid overlooking the cost elements that significantly affect the total LCC. This recommendation would also considerably accelerate the process of tracking down cost drivers.

A cost driver is basically an activity measure that serves as a basis for the activity's cost allocation. For example, the number of inspections and type of inspection could be a cost driver for a system quality assurance activity, but the cost drivers may be attached to different units of costs. When several cost elements are similar in respect to their cause-and-effect relationship, these elements can be pooled and represented with a homogeneous cost driver(s). At this point, cost allocation should be made based on the degree of correlation between the consumption of the activity and the consumption of the cost driv-

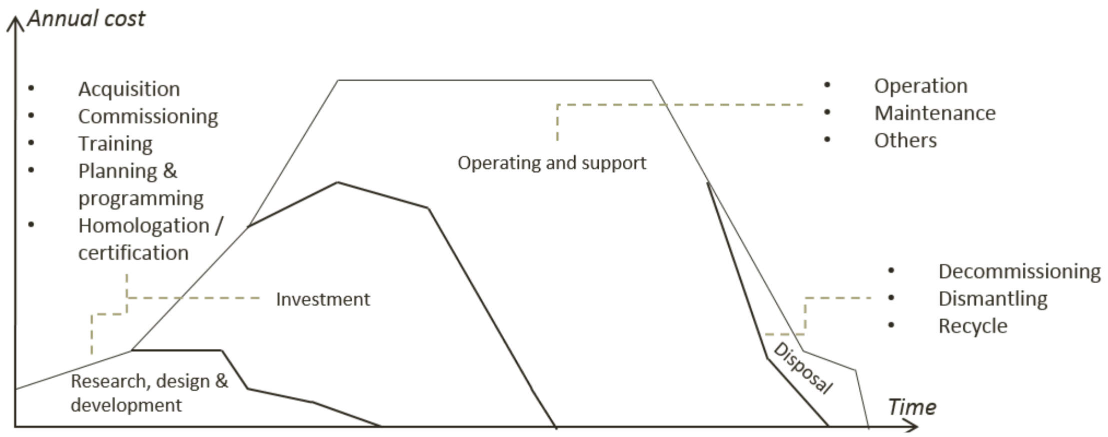


Figure 1 An illustration of notional profile of annual activities expenditures by major phases (cost categories) over a system life-cycle cost. The pattern shown is only for illustrative purpose, the actual curve will vary from one system to another. Adapted from (Obrenovic et al. 2006; Office of the Secretary of Defense 2014).

er. The accumulated cost incurred for a specific group of activities is known as the cost activity pool. To gain insight about the deviation in total LCC of the baseline design/system due to the changes in system objectives, a sensitivity analysis on the identified cost pools is recommended.

3 TRACK INSPECTION COST

Railway track components have long life spans and once installed, they are very costly and complicated to be modified from the initial design. To ensure that the asset can be sustained with high availability demands from train operators who request for different train paths and time slots, it becomes the asset owner's responsibility to deliver effective maintenance strategies. This goal can be achieved through careful design of inspection regime.

Fundamentally, there is not much deviation in respect to the maintenance of LCC models in whichever industry that homes the system of interest. The only thing that differentiates the models is the cost breakdown structure depending on managerial viewpoint, which is domain dependent. For railway track maintenance, the breakdown and identified cost drivers shown in Figure 2 are an adaptation of those used in (Nissen 2009) with simplification and/or addition from (Thoft-Christensen 2012; Stenström et al. 2016).

For every preventive maintenance (*PM*) cycle (see Figure 3), generally, a track is assumed to receive a minimum of m_I inspections under a periodic interval, say it, τ. Note that, value of these parameters are non-fixed throughout its service life time. Given a vector of business model parameters $\vec{v}$, the estimated inspection cost $\tilde{I}_{PM}$ is thus computed from the generalised equation given by (Stenström et al. 2016):

$$\tilde{I}_{PM}(m_I, \tau, \vec{v}) = m_I(\tau)\tilde{I}_{PM}(\vec{v}) = m_I(\tau)\left\{C_L^I(\vec{v}_1) + C_B^I(\vec{v}_2) + C_G^I(\vec{v}_3) + C_M^I(\vec{v}_4)\right\} \quad (1)$$

where $\bigcup_{\forall i} \vec{v}_i = \vec{v}$ and m_I are conditioned on τ. Briefly, conducting short inspection intervals enables more frequent inspections to be carried out in which up-to-date information about the condition could increase an opportunity of defect detection. Nevertheless, railway infrastructure companies have to assign a minimum value for m_I due to their limited resources and a large size of network to inspect. Similarly, both maintenance repair costs can be derived from Eqn.(1).

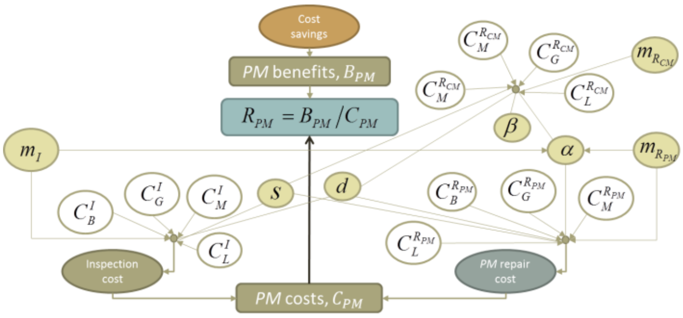


Figure 2 Major cost elements and drivers related with preventive track maintenance. At least one inspection is required otherwise the C_{PM} is solely dependent upon R_{PM}. Note that, C_x^y takes $x \in \{B$: labour, G: logistic, M: machine & materials, L: business loss$\}$ and $y \in \{I$: inspection, R_{PM}: *PM* repair, R_{CM}: *CM* repair$\}$.

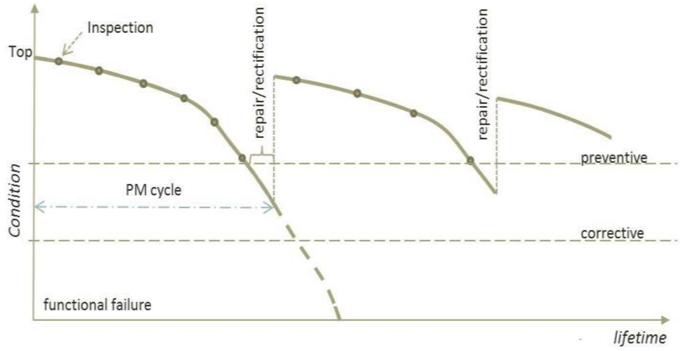


Figure 3 Distribution of inspection time points over different *PM* cycles. Note that, the final inspection is normally near to the preventive maintenance limit. A planned maintenance should be undertaken before asset condition beyond the corrective limit, otherwise benefit of inspection would decline.

4 THE INDICATOR

4.1 *Formulation*

Inspection is preceding tasks/jobs in a condition-based maintenance strategy, in which it is normally assigned periodically until a potential failure in the regarded object is detected. Under normal circumstances, a sequence of inspections is planned under uncertainty, thus in an unavoidable situation, a disruption is plausible. To redesign one or more inspection schedule(s) regardless of source and/or type of disruption, an additional investment that is partially or completely paid off by the benefits from the recovery action should be assessed.

In any profit-oriented organization, the ratio between investment benefits and incurrence costs is a primary and widely accepted analysis tool for financial profit assessment. In respect to preventive maintenance, the ratio for each finite *PM* cycle can be evaluated from the following:

$$R_{B/C}(t_o \rightarrow t_n) = \frac{B_{PM}}{C_{PM}} \equiv \frac{\alpha\beta C_{CM}}{I_{PM} + \alpha\widetilde{C}_{PM}} > 1 \tag{2}$$

where α and β represent the probability of defect detection and likelihood of asset condition having a sudden shift, respectively. Both parameters have values in the interval $(0,1)$ which leads to $\alpha\beta < 1$. Intuitively, the ratio of I_{PM} to R_{CM} is isolated into one side of the equation by rearranging Eqn.(2) in the following order:

$$\frac{I_{PM}}{C_{CM}} + \alpha\frac{C_{PM}}{C_{CM}} < \alpha\beta < 1$$

$$\frac{I_{PM}}{C_{CM}} < \alpha\left(\beta - \frac{C_{PM}}{C_{CM}}\right) < 1 \tag{3}$$

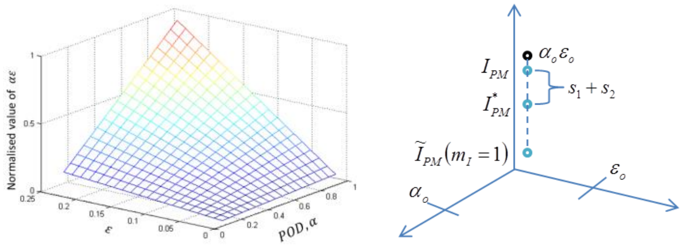
This decision leads to the constraint $\beta - \frac{C_{PM}}{C_{CM}} > 0$ which can be rearranged into $\beta > \frac{C_{PM}}{C_{CM}}$. Taking into consideration that β is a highly uncertain parameter thus, it is important to keep its value near to $\frac{C_{PM}}{C_{CM}}$ which provides an insight to authors to propose a deviation function $\varepsilon = \beta - \frac{C_{PM}}{C_{CM}} > 0$. Update Eqn.(3) with the definition of ε, we have:

$$I_{PM} < \alpha\varepsilon C_{CM} < 1 \tag{4}$$

From Eqn.(4), it is obvious that $\alpha\varepsilon C_{CM}$ can be interpreted as an upper limit of monetary resources that can be invested for inspections in one *PM* cycle considering the condition that $R_{B/C} > 1$ needs to be satisfied throughout the cycle. For various selections of α and ε, a mesh plot associated with Eqn.(4) is provided in Figure 4. Generally, an inspection schedule that is expected to deliver m_I periodic inspections at fixed τ satisfies the $R_{B/C} > 1$ condition if its I_{PM} lies under the mesh.

4.2 *Reschedule or not?*

From Eqn.(4), the effect of inspection interval changes on the benefit-cost ratio is unclear for quantification. This is a difficult situation in order to justify the direction in which a decision of inspection rescheduling would lead us to. However, as mentioned earlier, an inspection interval adjustment might change the assigned number of inspection. If this is the case, the corresponding inspection cost should be recalculated accordingly, refer to Eqn.(1), which brings back our attention to Eqn.(4). For any pair of $(\alpha_o, \varepsilon_o)$, an inspection schedule remains economic feasible as long as the position of an updated inspection cost I^*_{PM} due to an introduction of a new pair of (m^*_I, τ^*) is below the initial I_{PM}, as illustrated in Figure 4(b). To investigate the magnitude of changes allowed in I_{PM}, we revisit Eqn.(1) and update it with relevant reschedule costs.



(a) (b)

Figure 4 Indicators of feasible reschedule solutions. a) Upper bound of inspection costs, b) Permitted additional investment.

In the context of track maintenance, inspection reschedule requests might incur both track possession cancellation charge s_1 and the cost of new possession order s_2. Consider m^n_I out of m_I will be rescheduled over the remaining period of *PM* cycle, the $\widetilde{I}^*_{PM}$ is estimated as follows:

$$\begin{aligned}\widetilde{I}^*_{PM} = {} & \widetilde{I}_{PM}\left(m_I - m^n_I, \tau, \vec{v}\right) + \\ & \widetilde{I}_{PM}\left(m^n_1, \tau^*, \vec{v}\right) + (s_1 + s_2)\end{aligned} \tag{5}$$

Thus, $s = s_1 + s_2$ is the additional monetary cost incurred to an overall inspection cost due to inspection reschedule. Overall, any inspection schedule with I_{PM} positioned at higher coordinate from (α, ε)-axis has more opportunity to adjust the original inspection interval as long as the change does not increase the number of inspection. The possibility of violating the $R_{B/C} > 1$ condition due to periodicity change is substantially increased for the front edge area (blue area) in Figure 4.

4.3 *Reschedule cost*

As illustrated in Figure 4(b), a reschedule cost is necessary for the proposed indicator, and can be obtained by adding a cancellation cost from the booked possession to the cost of new possession order. Cancellation possession returns the affected track slot(s) to the train timetable. Based on this, a refund from the past possession cost to IM would be delivered and the amount can be conveniently derived from the track possession cost function. Hence, $s = -\eta_f q'(j) + q(j)$ where the $q(j)$ is the cost of accessing a track within the time band *j*. Possession time has a significant effect on the cost calculation due to variability in the number of passenger journeys over, a day and week and season (Famurewa et al. 2013). This can be observed from an existing train ticket structure; peak, off-peak and season ticket type. Meanwhile, the η_f denotes a notification factor of sending a cancellation order(request).

The base formula for calculating the track possession cost is given as follows (Halcrow 2013):

$$q(j) = t_p \times MRE \times n(j) \qquad (5)$$

where t_p and $n(t)$ denotes length of possession time (in minutes) and the average number of passenger journeys during time band *j*, respectively. The Marginal Revenue Effect (MRE) is the amount of long term revenue estimated to be lost by a passenger operator from one minute of lateness per passenger journey (Halcrow 2013).

For train journeys less than 20 miles commuting under the category of non-London regional flow, the MRE by ticket type can be calculated using the following equation (Wardman & Batley 2014):

$$MRE_g = (3.0 \times -1.04)/40 \times rev_g \qquad (6)$$

where rev_g is revenue per passenger journey by ticket type $g = 1,2,3$ represents three ticket types, namely, full (peak time), reduced (off-peak) and seasons.

5 AN EXAMPLE

This section aims to demonstrate an applicability of the proposed indicator. Any reschedule decision is considered economically feasible if the corresponding reschedule cost has a negative value, i.e. $s < 0$. Two possible scenarios of track inspection reschedules are delivered; 1) from weekday afternoon off-peak to the weekend, and 2) from a weekday afternoon off-peak to weekday morning off-peak. Table 1 displays the values used to calculate the Eqn.(6).

For the first reschedule scenario, reschedule costs for single and two track inspection decisions over four values of refund rate are displayed in Figure 5(a). Clearly, the cost significantly decreases as the number of inspections to be rescheduled increases. The trend of change is observed in all refund rates. No feasible solution can be achieved with an option to reschedule a single inspection decision. Nevertheless, at a refund rate of 0.85, the reschedule process is cost effective with two inspection decisions.

From Figure 5(b), which corresponds to the second scenario, regardless of the refund rate, reschedule one or two inspection decisions are ineffective for the existing track inspection schedule. Obviously, the schedule will suffer an increment in overall costs due to inspection rescheduling.

Table 1 Assigned values for Eqn.(6)

Item		Value	Ref.
Admin fee (£/order)		300	n/a
Notification factor	η_{f1}	0.5	(Halcrow 2013)
	η_{f2}	0.68	
Refund rate (%)		70:5:85	n/a
Regional revenue per passenger journey, £/journeys		5.40	(UK Office of Rail and Road 2017)
Average passenger journeys	Weekday morning off-peak	1558	(National Statistics 2017)
	Weekday afternoon off-peak	1025	
	Weekend service time	585	

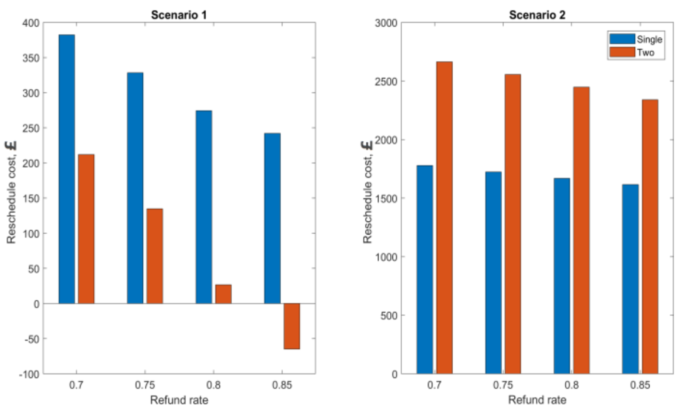


Figure 5 Effects of a refund rate and number of inspections in the reschedule cost function

6 CONCLUSION

In this study, the application of benefit-cost ratio has been extended as an indicator for track maintenance management in the situation where the assigned inspection schedule would require interval adjustments and/or frequency changes. Budget revision, inspection vehicle breakdown and worker strikes might trigger the need for rescheduling in the context of track maintenance. The mesh distribution related to the proposed indicator (refer to Figure 4) helps users to respond quickly whether adjustments on the inspection interval would drag an initial cost–benefit ratio out of the acceptable region. The indicator, however, requires a reschedule cost formulation to quantify an exact magnitude of deviation in the ratio. Based on the presented example, we have shown that the reschedule process requires at least two planned inspection decisions for cost effectiveness of operation. Overall, the proposed indicator is unique in the way it functions as a decision support tool and can potentially be extended for multi-inspection schedules.

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