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Execution time estimation of recovery actions for a disrupted railway track inspection schedule

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ABSTRACT: Track geometry quality is periodically updated upon arrival of new track measurements to maintain target levels of track reliability, availability, safety and ride comfort. The information chain for *n* consecutive track segments could be temporarily discontinued beyond the nearest inspection time in the occurrence of disruptions. This situation demands immediate but feasible recovery action(s) to avoid losing the reserved track possession(s) while maintaining railway line operational safety. Not only would a penalty of cancellation possession be imposed, but the disrupted schedule may also trigger other consequences such as cascading track component failure and train delay. While reputation at the organization level has better value today, maintenance departments should avoid overdrafts to pay recovery costs but use profit gained from affected track segments. In line with this goal, this study develops an optimization model based on track profitable capacity and reliability to estimate the time when a recovery action should be ideally executed. Operational reliability of *n* track segments subject to a sudden change/shift in track condition degradation path is evaluated according to consecutive *k*-out-of-*n*: a *Failure* system model. Simulation results highlight that as disruption time approaches the nearest inspection time, the execution time of recovery action decreases where the corresponding proportionality constant is determined from the track capacity per unit time. Based on the results, the proposed model would be a valuable decision-support tool for managing a disrupted track inspection schedule.

1 INTRODUCTION

Safety of trains and railway track performance are prompted by the permitted track maintenance plan. Despite its clear important, a railway infrastructure manager (IM) faces a great challenge almost every year to establish an effective maintenance plan which covers inspection, rectification and renewal works. Train timetables are given priority to maintenance and renewal works in track possession. This long-run policy states that track possession for maintenance works is allocated last when the identified tracks are unattended by both passengers and freight trains unless IM is willing to pay a compensation to an affected train timetable e.g. train cancellation and/or delay charge (Network Rail 2008). For instance, Network Rail receives a charge bill of more than £37 million for both planned and unplanned maintenance operations (Network Rail Limited 2016). Despite several attempts that have been made to design an integrated operational and maintenance plan, the complexity of the 'new' maintenance planning formulation; however, demands for sophisticated algorithms, which is a new group of human experts and high-end computer software and hardware (Herrmann et al. 2014).

Apart from track possession-related constraints, unplanned maintenance (UM) is another performance killer in track maintenance. UM occurs when a maintenance work has to be performed in advance of its original plan, which is typically due to late (or missed) detection of potential failure in railway track (or track components). This flaw has a strong link to an inspection; an input source of condition-based maintenance, where a disruption may inflict such degree of deterioration in the performance of inspection (Osman et al. 2016).

An occurrence of disruption is highly unpredictable, thereby indicating that a need for a reactive action is suffice. IM may have a repository of reactive actions to respond on different types of disruptions (Cacchiani et al. 2014). However, real-time assessment is required to determine an appropriate time to execute a predetermined action/plan. In fact, a recovery action still requires a preparation so that identified resources can be allocated effectively when a disruption occurs. In respect to track inspection, a recovery action could avoid losing the booked track possession. Otherwise, a disruption may trigger serious consequences e.g. a train delay which has the largest share of UM cost (Stenström et al. 2015; Ishak et al. 2016). Therefore, interruption in train and freight timetables would be the last resort of action to manage a disrupted inspection.

Track inspection frequency and interval are determined with subject to track reliability and profitability (Khouy et al. 2014). In line with this policy, an estimation of execution time needs to be tailored to track maintenance thresholds and financial policy imposed in the organization. While reputation has better value nowadays, the maintenance department might choose to not make an overdraft but pay a recovery cost using a profit gained from the affected track section. As time taken to generate the necessary amount of money is crucial, this idea should give concern on track possession loss that would cause performance of asset management to drop below the target (Network Rail Limited 2016).

Under the assumptions, an execution time of recovery action could be estimated by determining the earliest time when the profit is sufficient to pay for (estimated) costs incurred from the selected recovery action. This information is crucial to filter out infeasible solutions i.e. a recovery action cannot be performed before an inspection time. In light of the above, a micro-scaled profitability model of railway has been approached from a point of view of disruption management in order to derive an estimation model of execution time for a disrupted on-board track inspection.

2 THE ESTIMATION MODEL

Over an operation period (t_o, t_m) a profit from a track section denoted by $\tilde{P}$ can be estimated from following mathematical model (Khadem et al. 2010; Vaurio 1994):

$$\tilde{P}(t_o, t_m) = \int_{t_o}^{t_m} (c_a x - c_b) g(x) dx \quad (1)$$

where $g(x)$ is probability density function of random variable X which represents the length of time taken for an aggregated track geometrical index (TGI) of a track section passed the alert limit from a restoring point e.g. prior tamping maintenance. TGI is a numerical representation that is assigned to each track section as an input for track maintenance decision. The parameter c_a and c_b represents the profit per unit time while the track section is operating, and the penalty cost if train delay, cancellation or a temporary speed restrictions has to be applied on a track section, respectively.

When a track inspection is planned at time, t_{ins} somewhere within an operation period, the profit model in Eqn.(1) can be written in the additive form, and is therefore given by;

$$\tilde{P}(t_o, t_m) = \int_{t_o}^{t_{ins}} (c_a x - c_b) g(x) dx - c_{ins} + \int_{t_{ins}}^{t_m} (c_a x - c_b) g(x) dx \quad (2)$$

where c_{ins} is a total cost incurred for single execution of track inspection. In an occasion of a disruption, for instance it happens at time t_d, assuming that $t_d < t_{ins}$, the first part of model $\tilde{P}$ can be expressed in the following expression;

$$\tilde{P}(t_o, t_{ins}) = \tilde{P}(t_o, t_d) + \tilde{P}(t_d, t_{ins}) = \int_{t_o}^{t_d} (c_a x - c_b) g(x) dx + \int_{t_d}^{t_{ins}} (c_a x - c_b) g(x) dx - c_{ins} \quad (3)$$

At the time a disruption is acknowledged, the affected track section has actually survived without failure over time duration between t_o and t_d. In this scene, the parameter c_b in an integrand of the first part of Eqn.(3) is no longer valid and can be removed. Thus, the formula of profit calculation over (t_o, t_{ins}) period is given as follows:

$$\tilde{P}(t_o, t_{ins}) = c_a t_d \int_{t_o}^{t_d} g(x) dx + \int_{t_d}^{t_{ins}} (c_a x - c_b) g(x) dx - c_{ins} \quad (4)$$

As we mentioned earlier, at the time a recovery plan is executed, for instance t_r the size of profit must greater than the recovery cost, and this condition is expressed below:

$$\tilde{P}(t_o, t_r) \geq c_r(t_r) \quad (5)$$

where $c_r(t_r)$ represents a time-dependent recovery cost function. By solving a constrained optimization problem given in Eqn.(6) which is derived from Eqns.(4-(5) for t_r a position of t_r in the time line; either in (t_d, t_{ins}) or (t_{ins}, t_m) i.e. $t_r \in \{(t_d, t_{ins}) \cup (t_{ins}, t_m)\}$ can be determined.

$$\underset{t_d < t_r < t_{ins}}{Min} \left| c_a t_d \int_{t_o}^{t_d} g(x) dx + \int_{t_d}^{t_r} (c_a x - c_b) g(x) dx - (c_{ins} + c_r(t_r)) \right| \quad (6)$$

3 A TEST CASE

The estimation model was tested in the case of on-board track geometry measurements. A track recording car (TRC) measures and records a set of track geometric parameters in order to locate isolated defects and also assign an overall track condition. Contrary to a walking inspection which can divert off track at any location at any time, the TRC inspects track segments between two railway stations in a sequence order i.e. no overpassing. Assuming that $t_j; \forall j \in \{1,2,\ldots,n\}$ is an inspection time of track segment *j* throughout a track section, a condition of $t_1 < t_2 < \ldots < t_n$ is always true during the track possession.

A disrupted situation where the recording car temporarily breaks down due to unknown and unexpected mechanical failure is visualised. To respond to this situation, a maintenance department from the affected (administrative) area might request for an inspection vehicle from other areas to be temporarily used. Being fully aware of the fact that the request will incur costs (referred to a recovery cost) that depend on the time and duration the vehicle is needed, Eqn.(6) was solved to effectively handle a disruption. For that purpose, Eqn.(6) must be presented with a suitable $g(X)$ for an affected track section.

Due to the nature of TRC operation mechanism and tamping maintenance decision which are performed in a collective (grouping) mode, this study thus proposes a system reliability model to derive reliability (and unavailability) of track section.

3.1 *Reliability of track section*

TRC operates continuously within two stations i.e., track segments are inspected sequentially without overpassing. The nature of this mode of track inspection leads to the use of an aggregated level of track reliability as an input for schedule generation. On the other hand, when preventive tamping maintenance is decided, a cost-effective decision can be achieved by tamping consecutive track segments within one track possession time (Johansson, Per; Nilsson 2004). For that purpose, an evolution of TGI of track section is needed to be predicted to ensure the maintenance strategy satisfies track reliability and availability requirements (Patra 2007). On this basis, reliable operation of a track section must be presented and it can be computed based on system reliability model.

For illustration purpose, this study defines 1-km track section between two stops as a system of interest. The system is partitioned into five non-overlapping segments with equal length of segments. The system fails when two consecutive track segments had a rapid/sudden shift within one inspection interval. Thus, a reliable operation of the system is derived from consecutive *k-out-of-n*: *F* system. The proposed method in (Shmueli 2003) will be used for system reliability computation as it does not involve recursive computation. This features offers fast computation.

Prior computation, a probability density function of *X* which reflects characteristics of sudden shift in TGI's degradation path need to be presented. In our context of study, a sudden shift exhibits a situation in which TGI trespasses the first maintenance threshold faster (shorter) than an expected time (in-days). The description of this event fits a Gumbel (minimum) distribution. Thus, the corresponding probability density function is given by

$$f(X) = \frac{1}{\beta} e^{-\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\mu}{\beta}}} \tag{7}$$

where μ and β is mode value and scale parameter, respectively.

3.2 *Parameter settings*

In Eqn.(6), c_a, c_b and t_d are the main parameters that influence profit generation for a track section. To investigate relationship between these two parameters, the estimation model was tested on several c_a/c_b ratios over a range value of t_d under controlled simulations. For that purpose, values of other parameters remains unchanged and are listed Table 1.

Table 1 Parameter settings for Eqn.(6)

Parameters	Values
μ	100 days
β	9
c_a	[100:50:250]
c_b	800
t_{ins}	85
t_d	[67,84]

3.3 *Results*

Fig.(1 depicts the effect of the ratio of c_a/c_b over a range value of t_d on the earliest execution time t_r. The value of c_a/c_b ratio is varied from 0.125 to 0.375 with unit step 5/8. Obviously, for all considered ratios, as disruption time is approaching the inspection time, the length of buffer (or waiting) time of the execution becomes shorter. It means that a recovery action could be executed as soon as a disruption occurs at time $t_d \to t_{ins}$. For all considered values of c_a/c_b ratio except the $c_a/c_b = 0.125$, a feasible solution exists for every t_d. Nevertheless, the lowest ratio only provides a feasible solution if a disruption occurs around 4 to 10 days before t_{ins}.

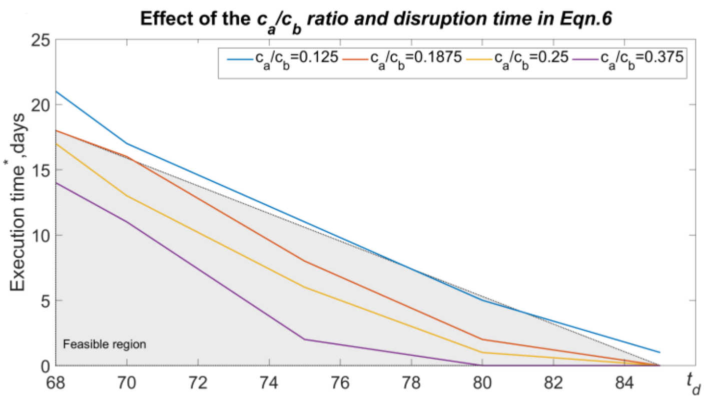

Fig.1 Downtrend trend in the execution time t_r.

Regardless of the time of disruption, a recovery action is always possible to be executed sooner in a case of high value of c_a/c_b ratio, as shown in Fig.1. This effect could be explained from the first component of Eqn.(4) in which a track profit calculation for (t_o, t_d) period is factorized by c_a. A larger value of c_a causes a track section to take lesser time to reach a recovery cost. It should be noted that, a disruption is an unexpected event and has no influence on assignment of c_a, which is strictly conditioned by supply-demand factor and transportation fair regulations (Office of Rail Regulation 2012).

4 CONCLUSION

Increasing number of worker strike, vandalism and terrorist attack, uncertainty in freight train demand, and decreasing availability of track possession raise the likelihood of disruption in on-board track inspection. The loss of reserved track possession which potentially inflicts unplanned maintenance is a direct consequence of disruption in track inspection schedule. This scenario urges any maintenance department to be more prepared in facing potential disruptions in the future.

In this work, we offer a decision support tool for managing disrupted track inspection. The tool integrating system reliability and railway profitability model supports decision maker(s) by providing an estimation of the earliest time for a recovery action to be executed without requiring an external financial support. Test results have proven that the proposed tool exposes an inverse linear relationship between the time of disruption and the execution time. Fast execution is permitted only when a disruption occurs near an inspection time and the corresponding time is conditioned by the ratio of c_a/c_b. However, this inference might not be valid with different system configurations i.e. other than 2-out-of-5 components. Further testing on the proposed estimation model should be carried out for generalization.

An implementation of recovery action might involve equipment, machine and/or man power supplied by external sources. Inclusion of availability of the resources into the model would be another extension of this work. We would expect significant changes in the properties of recovery cost function. Apart from that, an application of real data to the model would be a worthy effort to be pursued. The work could verify an assumption that we made on the distribution of times from an initial condition to the state of passing an alert limit. In addition, an initial assumption that all track segments in one section are identical unit can be further revised; whether from an identical to non-identical.

REFERENCE

Cacchiani, V. et al., 2014. An overview of recovery models and algorithms for real-time railway rescheduling. *Transportation Research Part B: Methodological*, 63, pp.15–37.

Herrmann, T., Control, T. & Vogel, T., 2014. Possession policies drive down maintenance costs. , (May), pp.64–67.

Ishak, M.F., Dindar, S. & Kaewunruen, S., 2016. Safety-based Maintenance for Geometry Restoration of Railway Turnout Systems in Various Operational Environments. In *Proceedings of The 21st National Convention on Civil Engineering*.

Johansson, Per; Nilsson, J.-E., 2004. An economic analysis of track maintenance costs. *Transport Policy*, 11(3), pp.277–286.

Khadem, M. et al., 2010. Profit-generating capacity for a freight railroad. *Transportation Research Record*, 7400(August), pp.1–17.

Khouy, I.A. et al., 2014. Optimisation of track geometry inspection interval. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(5), pp.546–556.

Network Rail, 2008. *Rail infrastructure cost benchmarking*,

Network Rail Limited, 2016. *Network Rail Limited's annual report and accounts 2016*, Available at: www.networkrail.co.uk/annualreport.

Office of Rail Regulation, 2012. *Periodic review 2013 consultation on schedules 4 and 8 possessions and performance regimes*,

Osman, M.H. Bin et al., 2016. Disruption: A new component in the track inspection schedule. In *2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*. pp. 249–253. Available at: http://ieeexplore.ieee.org/document/7588740/.

Patra, A.P., 2007. *RAMS and LCC in rail track maintenance*. Luleå University of Technology. Available at: http://epubl.ltu.se/1402-1757/2007/57/LTU-LIC-0757-SE.pdf.

Shmueli, G., 2003. Computing consecutive-type reliabilities non-recursively. *IEEE Transactions on Reliability*, 52(3), pp.367–372.

Stenström, C. et al., 2015. Preventive and corrective maintenance – cost comparison and cost–benefit analysis. *Structure and Infrastructure Engineering*, 2479(April), pp.1–15.

Vaurio, J.K., 1994. A note on optimal inspection intervals. *International Journal of Quality & Reliability Management*, 11(6), pp.65–68.