

Development of an integrated railroad track maintenance model

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ABSTRACT

In order for a railroad to function effectively, all aspects of the system should be maintained in good working order. Locomotives and rolling stock regularly move through areas where they can be inspected and maintained. However track does not move, so inspectors must traverse the line either on foot or in a rail mounted vehicle and maintenance crews must be sent to specific locations to make track repairs, which may not always happen before a service disruption. A track failure, due to either exceeding an industry or government specification or an acute failure, such as a rail break, can result in costly delays or even derailments with significant consequences. To help avoid such failures, it is beneficial for a railroad to be able to predict when and where failures might occur and then evaluate the relative costs and benefits of performing maintenance activities to ensure that the most cost effective actions are taken. Maintenance activities on North American railroads are currently prioritized based on the experience of track inspectors and infrastructure managers, many of who will be retiring within the next five years. To supplement this knowledge and help evaluate future changes in traffic beyond prior experience, a model is being developed to assist in the process of identifying and scheduling maintenance activities. The model consists of three primary modules: an integrated track quality and degradation module, a maintenance activity selection module, and a scheduling optimization module. The modules are either based on existing models or developed to fit the needs of the planning model, and are unique in forming a comprehensive maintenance model rather than looking at each step independently. It is anticipated that this model will result in decreased maintenance costs and improved safety due to the benefits of advanced maintenance planning and improved track reliability. A key area where this model could be implemented is in areas where shared high-speed passenger and freight operations are being considered and increased reliability is imperative, although any railroad could apply the model to their maintenance planning. In the former case, international experience in these areas could be beneficial for understanding how this process

can be applied. This paper will describe the concepts associated with each of the model components, how they are tied together, and the future research and collaboration potential for the project.

INTRODUCTION

A functioning railroad requires both infrastructure and vehicles to be maintained in working order. Locomotives and rolling stock regularly travel through facilities where inspections and maintenance can be performed (1), but infrastructure maintenance requires inspectors to traverse over 160 thousand miles of track in North America alone (2). Once potential maintenance activities have been identified, crews must still get track time to perform the required maintenance. This is a process that costs the North American Class I railroads millions of dollars each year (3).

The current maintenance planning process consists of a number of different procedures depending on the type of potential track defect. Some track parameters, such as crosslevel and warp, are specified by government organizations or the railroad and are monitored by track geometry vehicles. These parameters have two levels of defects, maintenance and critical. Once the maintenance threshold has been exceeded, track supervisors are made aware of it, and when the critical threshold has been passed, immediate action is required as prescribed by the Federal Railroad Administration (FRA) or internal track safety standards. This usually means downgrading the track to a FRA track class where it meets the specifications until remedial action can be performed. Other defects that cannot be monitored automatically, specifically rail breaks, require almost immediate remedial action when they are discovered due to FRA regulations (4). This local, reactive approach contrasts with larger scale track maintenance planning that is more centralized and based on input from local track supervisors. Typically, this planning process only entails comparing similar projects, e.g. rail renewal projects are only compared against other rail projects, not tie replacement projects, and the interaction of maintenance activities and benefits to all components of the track system is not always considered. The primary shortcomings of these methods is that they are either reactive or the selection procedure is not optimized and substantially subjective in nature. Some estimate that reactive maintenance is up to five times more expensive than proactive maintenance (5), and subjective methods can also result in sub-optimal decisions and unnecessary expense. Only comparing projects pertaining to a particular track component may result in a less effective maintenance activity being performed, or potentially multiple projects being done at the same time

when only one is necessary to bring the track condition to an acceptable level. Additionally, subjective methods make it difficult to transfer knowledge to future generations of railway employees.

Preventative maintenance planning can overcome these shortcomings by providing an objective framework to proactively plan and perform maintenance. This is done by using predictive models to estimate the future condition of the track and determine when maintenance needs to be performed (6). Since maintenance is being planned in advance, there is greater opportunity to coordinate maintenance and operations to reduce traffic disruptions while preventing the track from degrading to critical levels. Since the process is objective with established decision criteria, it will be easier to transfer knowledge as seasoned employees leave the work force. Additionally, considering all types of maintenance together in the objective analysis will ensure that the most cost effective track improvement procedures are performed.

While research has been performed on parts of the maintenance planning process or with a focus on a specific component, an extensive literature review did not reveal any models that cover the entire maintenance planning process from predicting track condition to developing a maintenance plan for the track structure as an integrated system. Considering the entire maintenance process allows for the model to consider interactions between components and when maintenance is performed. For example, performing subgrade and ballast improvements may allow for the rail in a track segment to remain in place longer. In order to fill this void, a model framework was developed to improve track maintenance planning.

The concept behind this model framework is to make decisions based on an objective, comprehensive view of the entire maintenance planning process and the track structure as a system. Therefore, the model framework presented here is comprised of three modules: track degradation, maintenance project identification and evaluation, and maintenance scheduling. The remainder of this paper will give more detail about the individual modules and describe how the model works.

TRACK QUALITY AND DEGRADATION

The first step of the track maintenance planning process is to determine the condition of the track at some future point when maintenance may need to be performed. Using statistical regression of historical track geometry data is a viable option for predicting the condition of some aspects of the track structure (7). Other aspects of track condition cannot be monitored in the same way, such as

internal rail defects that are removed almost immediately on discovery such that their gradual deterioration cannot be monitored in service conditions. For this latter group, theoretical models that could be applied to predicting the behavior of any type of track defect are required. Theoretical models also have the added benefit of being adaptable to changing operating conditions, which historical data may not accurately represent.

One model that is commonly used to represent the distribution of the time to failure for similar components including many aspects of railroad track is the Weibull distribution (8-14). Failure is defined in this paper as either the component having an acute failure, such as a rail break, or having a parameter of the track exceed track safety specifications prescribed by a regulatory body. Either of these situations will require trains to be stopped or slowed while repairs are made, and in a worst-case scenario, the failure may cause an accident with potentially serious consequences. The Weibull cumulative distribution function (CDF) is given in equation 1. As the name implies, the shape factor, α , determines the shape of the distribution, and the scale factor, β , is based on the average life of the component. The variable x is the age of the track or component measured in either years or accumulated traffic, with the latter expressed in units of million gross tons (MGT) (8,15,16).

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^\alpha} \quad (1)$$

Where:

α = shape factor

β = scale factor (MGT or years)

x = component age (MGT or years)

Although commonly used for failure analysis, the Weibull distribution may not be the best fit for all track defects, and models for each type of defect will need to be evaluated. Some desired characteristics of ideal degradation models include the ability to use actual track measurements to determine the track condition, consider the existing track condition as a starting point for the prediction, and evaluate the impact of incremental maintenance and interactions between components over the planning period. An ideal model will also have a basis in both mechanistic and empirical methods and focus on track parameters that may result in a service disruption such as surface alignment or rail defects. Component interactions need to be considered because the track is a system, and the performance of one part affects the others (17). For example, track with fouled ballast has a lower track modulus, and therefore higher rail bending stress, which, in turn results in

accelerated rail fatigue (18). However, if the model only looks at rail fatigue, the impact of a project to improve ballast condition may not be reflected in predictions of future rail condition, and maintenance such as grinding or rail replacement may be conducted prematurely. However, since the most developed of the available models only consider individual components (14,19,20), they could be adapted to the framework until better integrated models are identified. Utilizing mechanistic and empirical modeling allows for more precise predictions of the physical breakdown of track components while still taking into consideration the statistical variation in how the components degrade. For further discussion on mechanistic and empirical modeling see ADL (15), Yamashita and Hashida (21), and Duarte et al (22). Once the future track condition has been determined, it is possible for potential maintenance activities to be identified and compared.

MAINTENANCE ACTIVITY SELECTION

This module consists of identifying appropriate maintenance activities for a given defect and then comparing them to prioritize the most cost effective activities. One method for determining what maintenance should be performed is to have a baseline form of maintenance that would be used for the initial analysis, but more comprehensive maintenance could be performed based on professional judgment. For example, tamping would be the baseline maintenance activity, but undercutting could be performed as needed. However, this allows for subjectivity, and additional decision-making processes outside of the framework. Another more comprehensive approach that has been used in other similar transportation applications is case-based reasoning (CBR) (23-25). The concept of CBR is that the best alternative can be identified by comparing the current situation with a database of historical conditions, actions and outcomes. The model selects the method that historically has resulted in the best result for the lowest cost. As maintenance is completed and the resulting conditions are monitored, the database grows and predictions will become more accurate (25,26). This method could be beneficial for use in railroad track maintenance as various conditions require different treatments. For example, a crosslevel defect may be the result of differential ballast settlement or it may be a surface bent rail. The first situation would likely require tamping, but the latter would require undercutting and rail replacement.

After eligible maintenance activities are identified, they must be prioritized to ensure the most efficient and effective activities are performed first. One option is to compare the benefit-cost (B/C)

ratio for each project, similar to what was done by Liu et al (27) for evaluating potential track class upgrades. In order to consider the impacts of maintenance on both safety and train operations, the costs should consider both direct maintenance costs and operating costs due to train delay. Although data for direct costs would need to be gathered from operating railroads, a number of train delay calculators (TDCs) have been developed. Some TDCs depend on a given service outage and have annual tonnage as the independent variable (1), which would be suitable if the outage length was known and consistent. Since this is not likely to be the case, other models such as that developed by Schaffer (28) may be more suitable to this application. The selected TDC must be calibrated and validated to ensure that it is applicable to the railroad where it will be used.

The benefit of a given maintenance project is the service disruption risk reduction for a particular maintenance activity. Risk is defined as the probability of an event times the consequence of the event (29,30). Therefore, the benefit is the reduction in the probability of a service disruption multiplied by the expected cost of an incident. Various service disruption scenarios with different probabilities and consequences need to be considered for each maintenance activity. For example, if maintenance is not performed and the track exceeds the FRA track class specifications, the operational consequences of slow orders on the track that have a 100 percent chance of happening, while a derailment has a lower probability of occurring but potentially a much higher consequence. The higher cost of reactive maintenance compared to planned maintenance also needs to be considered. Using the Weibull distribution results in the track condition being represented by the probability of failure at a given component age, so the application of measurement based models requires the development of relationships between the measured track condition and failure probabilities. Traffic density should also be considered in the benefit calculation because the greater consequences of disruptions on a track segment with higher traffic will result in larger benefits from maintenance. Further research is needed to identify the effectiveness of specific maintenance activities at improving the track structure and directly reducing service disruption probabilities.

MAINTENANCE SCHEDULE

The third module selects projects and develops the maintenance schedule. For a single rail line, a variation of the knapsack problem with scheduling based on the geographic position of the selected maintenance activities could be sufficient. In a knapsack problem, activities are selected from a list

and are subject to budgetary and time constraints (31), and the optimization typically consists of maximizing the benefit while constraining the costs (31-33). To utilize the B/C ratio, a variation of this method could be used by weighting the activities based on the B/C ratio, while considering the time and cost to mobilize equipment between projects. This module should consider the direct maintenance costs since train delay will not be considered in the maintenance budget.

More complex networks will require more advanced routing models. One model that is ideal for this application is the track maintenance scheduling problem (TMSP) model. This model minimizes transportation and penalty costs while considering the effects of work windows, activity sequencing, and project clustering. A primary benefit of this model is that it was specifically developed for the railroad industry (34), which makes it well suited for this application.

MODEL OPERATION

For this model to work effectively, it must be able to consider the relative degradation of the track segments. One method is to execute all three modules for each year in the planning period. For this method, initially the track condition is projected to the end of the first year and projects are selected and scheduled as described above. This is repeated for the next year with the track condition at the end of the first year being applied as the new initial condition. That is, if maintenance is not performed then the condition of the track at the beginning of the next year is the predicted condition at the end of the previous year. If maintenance is performed during the previous year, then the condition is projected to the end of the year based on the improved condition and this is used as the starting condition for the next year. This is repeated until the end of the planning period. Another option is to use an iterative process that determines an initial schedule by projecting the track condition to the end of the planning period. The condition of the track at the scheduled times is determined and a new maintenance plan is developed. This would be repeated until the plan stabilizes. However, this issue could become moot if an entirely mathematical model was developed to envelope the entire process.

Regardless of how the model is operated, it is anticipated that the model would be run repeatedly during the planning period, as new information will be gathered from inspections and renewal projects. This will allow for continual improvement in the maintenance plan.

CONCLUSIONS AND FUTURE WORK

The model presented here has the potential to improve track maintenance planning by reducing costs while still maintaining a safe railroad. Considering the entire process in one model allows for improved coordination and prioritization of maintenance activities to make sure that the railroad is keeping the track safe in a way that objectively considers both costs and benefits. The framework of this model also offers a way to help transfer knowledge to future generations of railroad employees. As new information about track performance is developed and track and operating conditions continually change, the model can be updated as necessary to reflect these changes. The objective nature of this process will allow for easier knowledge transfer because it will not require extensive personal experience to make subjective decisions. However, field experience will aid in understanding how and why certain activities are done and ensuring the final maintenance plan is feasible.

Some future work has been described throughout the paper, but there are specific areas where additional work needs to be done to further progress the applicability of the model to actual rail operations. The identification of more advanced track and component degradation maintenance models will assist with making the maintenance planning model more robust and applicable. While review of literature will continue, efforts will be made to determine which, if any, models are used by North American Class 1 railroads. These will be validated and aligned with the needs of an operating railroad. In conjunction with this, research must determine the statistical relationship between track condition and service disruption probability to better understand the benefits that can be realized through particular maintenance activities.

Additional research will focus on determining the costs associated with various maintenance activities and determining their effectiveness at improving the track condition. This improved understanding will result in a better assessment of the B/C ratio, as well as allow for improved budgeting. This effort will include determining the time required to complete those maintenance activities for better time budgeting and schedule planning.

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