

**DEVELOPMENT OF AN INTEGRATED MODEL FOR THE EVALUATION AND PLANNING OF
RAILROAD TRACK MAINTENANCE**

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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 some industry or governmental 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. A model is being developed to assist in the process of scheduling and directing track maintenance work. The model consists of three primary modules: an integrated track quality and degradation module, a maintenance activity selection module, and a scheduling optimization module. By taking into account a wide range of costs and benefits, the model can help railroad infrastructure managers better account for risk and indirect costs such as track time, as well as account for the criticality of certain types of imminent failures. This paper will describe the inputs and outputs for the model, as well as detailing the concepts associated with each of the model components.

INTRODUCTION

In order for a railroad to function effectively, all aspects of the system needs to be maintained in good working order. Locomotives and rolling stock regularly move through areas where they can be inspected and maintained [1]. 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 service disruption is defined here as either the track exceeding some industry or governmental specification or an acute failure, such as a rail break. Either can result in costly delays, and an acute failure can result in derailments with significant consequences. To help avoid such disruptions, 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.

The use of predictive methods to plan maintenance and avoid service disruptions is known as preventative maintenance planning [2]. Executing early maintenance can save the railroad infrastructure owner from a more costly failure. One of the most obvious benefits of this method is the costs savings due to the avoidance of service disruptions because maintenance is performed before there is a failure. Other savings could be realized through increased coordination of maintenance activities and scheduling, which results in less track time being taken by maintenance crews. Additionally, a better understanding of component performance and degradation will assist in budgeting decisions since planners will have a better understanding of when expenditures will need to be made.

Preventative maintenance is especially important in shared corridor areas, since service reliability is paramount for a successful passenger railroad.

As a large portion of the railroad workforce is expected to retire within the next few years, preventative maintenance planning and scheduling will be more difficult to optimize unless the knowledge of experienced senior roadmasters and engineering department employees is captured and transferred to younger staff. A quantitative model for maintenance planning can assist new roadmasters and other infrastructure managers in determining when and where to perform maintenance despite not having years of experience. An extensive literature review revealed no existing comprehensive, quantitative maintenance planning models in the public domain despite there being financial analysis into the cost effectiveness of maintenance practices [3]. This paper will discuss the framework of a model that is being developed to assist in the process of planning and scheduling track maintenance work. The model consists of three modules: a track degradation module, a maintenance activity selection and evaluation module, and a schedule optimization module. The benefit of using independent modules is that as improved component models are found, they can more easily be integrated into the comprehensive model. This paper will describe the input requirements and model outputs, detail the concepts associated with each of the modules, and describe how the modules will work within the model framework. Currently, simplified models are being used to develop the model as a proof of concept until more sophisticated models have been selected and adapted.

TRACK DEGRADATION MODELING

The track degradation module consists of degradation models for each of the major track components (rail, ties, and ballast), which predict the component's condition at some future point in time. Much research has been performed in the area of track degradation, so existing models can likely be adapted to fit the larger framework of this research. The most basic type of degradation model is the component model, which is specific to a particular track component such as rails, ties, or ballast. Integrated models are more complex and consider the interactions between track components. This type of model is generally more representative because the condition of one component will affect how the others perform and degrade [4]. One example of this is that fouled ballast will result in a lower track modulus, which will result in additional rail bending stresses, and subsequently accelerated rail degradation due to fatigue [5]. Degradation models can also be divided by how the model predicts the degradation rate. One method is to model the physical reactions that are causing the degradation, which is commonly referred to as mechanistic modeling. Mechanistic modeling can be difficult as materials are not homogenous, and the interactions are either difficult to measure or, in some cases, poorly understood. *Another* method, commonly referred to as empirical modeling, is to model the statistical variation of how

the components will degrade and fail based on experimental or observed field data. However, the best approach is to take aspects from both of these procedures and model the statistical variation of the physical breakdown [6].

Currently, Weibull curves using values found in a literature review are being used for the degradation module until more complete models are identified. The Weibull curves were convenient for preliminary development because they only require two constants, the scale factor (λ) and the shape factor (α). Weibull curves are commonly used for representing the distribution of time to failure for a component, and the cumulative distribution function (CDF) is given as:

$$1 - e^{-(\lambda x)^\alpha} \quad (1)$$

The CDF represents the probability that a component will have failed at time x [6,7]. In the railroad industry, the time variable x could be measured in either years or in traffic (expressed as gross tonnage or MGT). The simplicity of the Weibull curves allows for initial development and testing of the module without attempting to account for more complex interactions and relationships that influence degradation. For the Weibull curves to be truly representative of the long-term behavior of a track section, the model needs to consider the effect and interaction of factors such as speed, axle load, track geometry, etc. and these relationships will be refined in later phases of this research. As more representative models become available, they will be adapted and integrated into the track degradation module. The focus of this effort is on finding models that represent track component properties and behavior that are directly related to track standards as these tolerances and measures correspond to derailment risk and the imposition of slow orders.

Research is ongoing to find models that are more robust and consider a wider range of variables. There are many models available, but it is necessary for the selected models to be able to output information that will be both useful for maintenance selection and indicative of the component condition at a given point in time. Some models give information about how long a component is expected to last [8-10] and some give the incremental damage based on a set of demands [4,11], but these do not give the option of considering maintenance or how to project component condition based on an imperfect starting condition. The ideal model for any component will consider a wide range of inputs, have an output that numerically describes the condition of the component with respect to some maintainable characteristic, be able to start at an imperfect condition, and has a combined statistical and mechanistic basis. The ideal model would also include measures of how effectively maintenance activities reverse the degradation process. Different maintenance activities performed on different components can have effects ranging from returning the component to a completely "new" undegraded state, removing a certain amount of "repairable" degradation while

leaving the component with some amount of permanent “irreparable” degradation history to finally not removing any existing degradation but only slowing the rate of future degradation. These characteristics would allow for the models to be able to more effectively predict future component condition and future maintenance requirements over time.

MAINTENANCE PROJECT SELECTION AND EVALUATION

The maintenance activity selection module, (i.e. selection of which maintenance activity is best for a given defect) has not been fully developed yet, but it is an important component as different circumstances will necessitate different maintenance. Maintenance project selection is an area that, compared to the other two modules, has not been the subject of as much research, and no applications to the rail industry were found in a literature review. However, some research was found that might be adapted for use in railroad maintenance planning. One method that has been used in other fields is case-based reasoning (CBR). CBR consists of having a case library that contains the circumstances and costs for various past projects. The CBR system compares any new situation to the case library to determine new solutions and determine the costs of the project [12,13]. A CBR system would be useful for railroad track maintenance as not every track issue calls for the same treatment. Some examples would be if rail wear and fatigue crack density was sufficient to require rail replacement rather than grinding or if the entire track structure was at a point where out-of-face replacement became economical. Currently, the model has a probability threshold that is used to determine if maintenance needs to be performed (i.e. if the degradation level reaches or exceeds 60% chance of failure, then the maintenance will be performed, otherwise it is left out of the project selection analysis). This threshold is important because a project should not be considered unless it will substantially improve the state of the track. Performing maintenance just to use the budget money may reduce the life of the track. One specific example of this is the ballast, where tamping degrades the ballast, and should only be performed when necessary in order to keep the ballast in optimal condition [14].

After maintenance activities are selected, the model needs a way to evaluate and select which maintenance projects to perform. This is similar to the knapsack problem, where there are several projects that can be selected from, but only a select number can be performed based on budgetary and time constraints [15]. Typically, the method for selection consists of maximizing the benefit while constraining the costs [15-17]. A variation of this method is used in the model in order to allow for the maintenance plan optimization module to make the actual project selection based on the time and costs required to mobilize, perform a project, demobilize and reposition to the next project site. To facilitate this, the benefit-cost ratio (B/C) for each proposed project is calculated, which the model can

use to rank the projects in order of their efficiency. This method is similar to that done by Liu et al for analyzing the cost effectiveness of upgrading track class in a route segment to reduce derailment risk. In their analysis they calculate the net present value of the savings based on the risk reduction and the cost to upgrade and maintain the track [18].

The costs of the maintenance projects consist of the direct cost of performing the maintenance and the indirect cost of track time. The direct cost of performing maintenance includes the cost of labor, equipment, supplies and materials. These direct unit costs are fairly constant for a given maintenance activity as the equipment and labor rates should have little geographic variation across a particular railroad network. Variability is introduced with the amount of work to be performed, which can influence the type of equipment and amount of labor for a given maintenance activity and the corresponding production rate. However, the cost of track time will show significant geographic variation as it is heavily dependent on the volume and type of traffic moving over a line that will be disturbed by the maintenance activity. On a low-density line, track time will have relatively little cost and impact to operations, but on a passenger route or a line with high value freight and/or high traffic volumes, the costs of interrupting operations for maintenance will be much higher. By using track occupancy costs, the effects of maintenance on track capacity can be considered. A high-density line will have a much higher occupancy cost than a lower density line, but as will be discussed later, the consequences of a service disruption due to a deferred maintenance activity will be higher as well.

The benefit of maintenance is defined in this research as the reduction in risk of a service disruption such as a derailment, detected component failure, or a slow order. Risk is given as the probability of an event times the severity or consequence of the event [10,19]. Therefore, the benefit is the reduction in the probability of a service disruption multiplied by the expected cost of the incident. The risk reduction is directly related to the efficiency of a particular maintenance activity at restoring a component to a safer state. A literature review was unable to reveal any research into the effectiveness of maintenance activities, so currently the model assumes that the maintenance activities return the component to a probability of failure of zero. While this is not an accurate assumption, it was made to simplify the development of the model framework.

Currently, the rating of the track components indicate the probability of failure, and the cost of a derailment incident is placed at \$3,000,000 based on an analysis of ethanol tank car accidents from 2001 to 2011 [20]. This value will be adjusted as further analysis is completed to allow for variation of lading on a line and variation of risk. While this value may be high for some disruptions, it was a reasonable starting point as the value was readily available from past research. As mentioned above, the risks for a higher density line will be higher because the increased traffic will increase the probability of an accident, and the resulting accident or slow order will delay more trains and increase the consequence [1]. Other issues, such as

population density or the amount of hazardous materials shipped along a line will increase the consequences of a derailment as a hazmat accident will likely require evacuation, and a high population density will require the evacuation of more people. The risk of a derailment is a function of a variety of inputs including train length, speed, and track class [21-25], so any analysis should consider these inputs in addition to the track condition, which is the risk reduction factor that is of primary concern for this model.

Currently the model does not consider the impacts of slow orders as the degradation models do not give values that are directly relatable to the FRA track class restrictions. As more descriptive degradation models are adapted, the model will consider the costs of slow orders due to track class restrictions and compare the delay from slow orders to the risk of an accident.

MAINTENANCE PLAN OPTIMIZATION

The third module optimizes the proposed maintenance plan via a knapsack analysis. It considers the timing and location of the identified maintenance projects in order to ensure that there is sufficient time and budget to perform the maintenance. It maximizes the benefits, through the surrogate of B/C, such that the sum of the maintenance times and the time to travel between jobs is less than the available time, and the sum of the maintenance cost is less than the annual budget. It is important to note that the maintenance costs mentioned here should not include the track occupancy costs since they are not directly billed to the maintenance budget. This is another area where extensive research has been performed, so new models will not need to be developed, and existing models will be adapted to fit within the framework described here [26,27].

MODEL OPERATION

The model operation consists of two main parts: the initial run and the iterations. The initial run consists of going through all three modules to determine an initial maintenance schedule based on predicted track condition at a given time horizon. However, this schedule does not consider the cumulative effect of projects as they are scheduled and thus won't always represent the actual conditions when the maintenance is performed. For example, the degradation module determines the condition of the track components after five years, and that condition is what is used to select the initial set of maintenance activities. However, if the model schedules a maintenance activity to be performed in the first year, then the track will be in better condition than predicted, and may not need maintenance at that time. To resolve this issue, the model will iterate the optimized set of maintenance activities until a stable solution is reached. The first step is to take the maintenance plan that is produced by the third module, and, given the set of selected activities, determine what degradation period actually needs to be considered. With these new input parameters, the

model runs through all of the modules again to see if the schedule changes. This process is repeated until the maintenance schedule stabilizes.

The iterative solution process allows for a balance between over-maintaining the track, which results in additional costs and potentially reduced life, and deferring maintenance, which can result in a shortened component lifespan and increased probability of an accident. On some lines it may actually be more cost effective to defer maintenance until there is a higher likelihood that it will fall below FRA track standard requirements because the types of traffic that run on the line are low risk and may not be very sensitive to delays. In other cases, maintenance is typically performed on a routine cycle, but this may result in improper maintenance timing due to variation in loads or speeds, e.g. a passenger line and a heavy-haul freight line would not need to be on the same grinding cycle since equivalent MGT on the passenger line will have different effects on the rail than the freight line [28].

FUTURE WORK

Much of the future work has been described throughout the paper, but there are some specific areas where additional work needs to be done to further progress the applicability of the model to actual case studies. The identification of more advanced track and component degradation maintenance models will assist with making the maintenance planning model more robust and applicable. While continued literature review will take place, efforts will be made to acquire the models used by some North American Class 1 railroads as these models will be validated and likely be aligned with the maintenance needs of a Class 1 railroad. Analysis will be performed to determine the probability of an accident or delay based on various factors. This will improve the risk analysis to determine the B/C ratio, and make the model as a whole more applicable for use. In general, work will be performed to improve the robustness of the model to ensure that it accurately represents maintenance activities.

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