An Integrated Model for the Evaluation and Planning of Railroad Track Maintenance

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ABSTRACT

Each year the North American Class 1 railroads spend billions of dollars on track maintenance. Even a small percentage reduction in maintenance costs, could save the railroads millions of dollars. Of course this is only feasible if cost reductions can be accomplished without decreasing the safety, utility, and robustness of the railroad track infrastructure. One way to reduce maintenance costs is to implement an effective preventative maintenance plan, which can allow for advanced scheduling of maintenance activities and more effective prevention of service disruptions. To assist railroads in developing such plans, a preventative maintenance planning model was developed. The model can assist in the identification, selection, and scheduling of maintenance activities to allow for an optimal balance between conducting preventative maintenance early before issues arise and deferring maintenance activities until critical risk thresholds are met or exceeded. This optimal balance is achieved by the model while considering budgetary constraints, resource constraints, and the geographic distribution of projects and resources across the rail network over an appropriate time horizon. The model consists of three modules: track degradation, project identification and evaluation, and maintenance scheduling. This paper will describe the framework of this model along with the structure and workings of the component modules.

INTRODUCTION

For a railroad to operate effectively, all aspects of the system must be maintained in working order, and North American railroads spend millions of dollars each year on maintenance (*1*). Locomotives and rolling stock regularly move through areas where they can be inspected and maintained (*2*). For track, however, inspectors must traverse the line, and maintenance crews must travel to specific locations to perform maintenance. Maintenance can be performed either reactively or proactively, known respectively as corrective and preventative maintenance. Corrective maintenance consists of waiting until a component has failed and then performing maintenance (*3*,*4*). A failure is defined in this context as either the track exceeding a tolerance specified by a railroad or regulatory body or an acute failure, such as a rail break. Either of these will disrupt service through trains being stopped or slowed and can result in costly delays. Additionally, acute failures can result in derailments with significant consequences. Corrective maintenance has the benefit of ensuring all of the component's utility has been used by deferring maintenance as long as possible. This can result in increased costs because of the above mentioned service disruption costs and the fact that, since it is unknown exactly when a component will fail, maintenance crews may need to be dispatched at a time when they are not prepared or convenient to the area. Corrective maintenance is unavoidable to an extent, but should be minimized because of these additional costs. Alternately, preventative maintenance consists of performing maintenance either on a predetermined schedule or once the component reaches a certain condition in advance of reaching failure or allowable tolerances (*3,4*). This has the potential to improve planning so maintenance is performed when it is most convenient and cost effective, but it may result in premature component replacement and reduced component life from maintenance being performed too frequently. Some estimates show that preventative maintenance has the potential to reduce costs by as much as 80 percent over corrective maintenance (*3)*. Current practice is a combination of corrective and preventative maintenance; a maintenance threshold is set to indicate that a failure may occur soon and maintenance should be performed to prevent the failure. However, this is still a reactive process, as maintenance is not scheduled prior to the threshold being reached. Advanced preventative maintenance planning can improve maintenance procedures by using predictive models to estimate the future condition of the track and determine when maintenance needs to be performed (*5*). This approach seeks to realize the full benefits of preventative maintenance by optimally scheduling maintenance activities to reduce and balance the amount of premature maintenance against the need for reactive responses to maintenance thresholds.

In addition to the performance benefits of preventative maintenance, an improved understanding of how the track is degrading will aid in budgeting decisions since planners will have a better understanding of when capital and maintenance expenditures will need to be made. This paper will discuss a model framework that is being developed as a tool for track maintenance planning.

MODEL OVERVIEW

While research has been performed on parts of the maintenance planning process, an extensive literature review did not reveal any comprehensive models that cover the entire maintenance planning process from predicting track degradation to developing a maintenance plan. Considering the entire maintenance process is important because the track is a system and improvements on one component will affect how others perform in the future. For example, improving the track substructure may alleviate the need to replace the rail.

As mentioned above, the purpose of this model is to make decisions based on a comprehensive view of the entire maintenance planning process. Therefore, the model framework presented here is comprised of three modules: track degradation, maintenance project identification and evaluation, and maintenance scheduling. The reason for the modular framework is to enable the model to consider the entire process, while allowing for the individual modules to be updated without significantly impacting the rest of the model. The remainder of this paper will give more detail about the individual modules, describe how the model works, and provide a case study.

TRACK 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. This is done through a track degradation model that predicts the condition of the track at a specified point in the future. For model development, a simplified degradation model based on the Weibull distribution was used, but more advanced models will be applied as they are identified or developed. The use of the Weibull distribution results in the track condition being defined as the probability of failure, which removes further assumptions of how the track condition relates to service disruption risk. When more advanced models are used, the track condition would be expressed through track measurements monitored by either track geometry cars, rail defect cars, or track inspectors that have a service disruption probability associated with them. The Weibull distribution is commonly used to represent the distribution of the time to failure for similar components including most aspects of railroad track (*6-12*).

One reason for selecting the Weibull distribution for use in the development of the model is its simplicity. The cumulative distribution function (CDF), given in equation 1, describes the percentage of the component population expected to have failed prior to a given age. The shape factor, α, determines the probability distribution and the scale factor, β, is based on the average life of the component. The variable x is the age of the track in either years or million gross tons (MGT) (*6,13,14*).

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

Where:
α = shape factor
β = scale factor (MGT or years)
x = component age (MGT or years)

The simplicity of the Weibull distribution allowed for initial development and testing of the module without need to consider some of the more complex interactions that influence track degradation. To realize the full potential of this maintenance planning model, more comprehensive degradation models will need to be used.

Ideal degradation models would comprise characteristics such as consideration for the existing track condition and the potential for incremental maintenance. Track degradation can be considered either by looking at the components separately or considering track component interactions. There are many models that represent individual track component degradation (*12,15,16*). However, since the track is a system and there are interactions between components (*17*), integrated models are important for representing how the track as a whole is degrading. For example, track with fouled ballast has a lower track modulus, which results in higher rail bending stresses, which, in turn results in accelerated fatigue (*18*). However, if the model only looks at rail fatigue, improving the ballast condition may not be reflected in predictions of future rail condition and maintenance such as grinding or rail replacement may be conducted prematurely.

Beyond the differences of viewing the track system on a component or comprehensive level, methods that can be used to model track degradation can be further divided into mechanistic and empirical models. Mechanistic modeling considers the actual physical interactions within materials or at component interfaces that cause degradation. This method can be challenging, computationally intensive and time consuming as materials are not homogeneous and the interactions at component interfaces may be difficult to measure or are poorly understood. Alternately, empirical modeling is statistical in nature and models are developed based on historical data. One major drawback of this method is that the model is only as good as the input data and not all combinations of possible input parameters can be found in the historical record. The optimal method for degradation modeling is a combination of both that allows for some consideration of the physical properties of the track structure while still taking into consideration the statistical variation of how the degradation will occur (*13*). Specific focus should be given to the track parameters that have the possibility of introducing a service disruption, such as FRA track class specifications or other potential derailment risks such as rail breaks.

MAINTENANCE PROJECT IDENTIFICATION AND EVALUATION

The maintenance activity identification and evaluation module identifies maintenance projects and then compares them against each other for a particular planning period with the aim of determining the optimal set of activities to consider scheduling. Currently, the model does not identify specific maintenance activities, but identifies where maintenance needs to be performed. Eligible maintenance is identified through maintenance and FRA thresholds. These are equivalent to similar values used in track geometry cars to determine when maintenance needs to be performed. Track segments that exceed those thresholds are defined as yellow and red defects, for the maintenance and FRA thresholds respectively. In the current formulation, these values represent the probability that a service disruption will occur at the internal maintenance threshold and at the FRA regulation tolerances, but as mentioned above further improvements will use track measurements with associated service disruption risks. For consistency, track segments that are below the maintenance threshold are classified as green defects since the track has degraded from its original new condition, but is not severe enough to warrant maintenance.

Part of the project identification process is selecting which maintenance activity is best to repair a particular defect. One method that is being investigated for use in this module that has been used in similar transportation applications is case-based reasoning (CBR) (*19,20,21*). The concept of CBR is that the best alternative can be identified by comparing the current situation with a database of historical conditions. The model selects the method that historically has resulted in the best result for the lowest cost (*21,22*). This method could be beneficial for use in railroad track maintenance as not every condition requires the same treatment. For example, a crosslevel problem 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. As maintenance is completed, the database grows and predictions will become more accurate.

After eligible maintenance activities are identified, the model evaluates them for comparison through the benefit-cost (B/C) ratio. The process used in this model is similar to that used by Liu et al for evaluating the cost effectiveness of track class upgrades (*23*). For this analysis, the costs include both direct costs and train delay costs. It is well understood that a key inhibitor to obtaining work windows is the density of the traffic on a track segment, and train delay costs approximate this. Due to a lack of data for analysis, the direct cost is determined by having a fixed cost added to a variable cost that is proportional to the track condition. More precise cost figures will be determined as data is acquired. The time to complete a maintenance project is also assumed to be proportional to the track condition. The cost of traffic delay is calculated in the manner developed by Schaffer (*24*). This method assumes a linear delay pattern, which may not necessarily be accurate, but other train delay cost calculators found were based on a given service outage length (*2*). As maintenance activities are identified, specific delay costs could be determined.

The benefit of a given maintenance project is calculated by the reduced risk of a service disruption given maintenance is performed. Risk is defined as the probability of an event times the severity or consequence of the event (*25,26*). Therefore, the benefit is the reduction in the probability of a service disruption multiplied by the expected cost of the incident. In order to consider the traffic levels, this value was multiplied by the number of trains that travel over the segment in one year. Since the improved failure probability is unknown, the user provides the maintained track condition.

The model currently considers derailments and component failures as possible service disruptions. Slow orders are a possible service disruption associated with exceeding FRA track specifications, but the impacts of slow orders are dependent on the track class, which is not currently considered.

MAINTENANCE SCHEDULE

The third module selects projects and develops the maintenance plan. This is another area where substantial research has been performed, and the model currently has a simplified procedure for development purposes. The model currently uses a process similar to the knapsack problem, where projects are selected from a list, and are subject to budgetary and time constraints (*27*). Typically, this method consists of maximizing the benefit while constraining the costs (*27,28,29*), but a variation of this method is used where preference is given to projects that will yield the highest B/C ratio, while considering the time and cost to mobilize equipment between projects.

The model gives preference to FRA defects, but if the budget isn't large enough to cover all of the FRA defects, then the track supervisors are responsible to maintain the track to within FRA tolerances. It should be noted that the costs used in this area are only the direct maintenance costs since traffic delays will not be accounted for in the maintenance budget. Currently, mobilization time and costs are fixed, but as more advanced models are applied these can be varied based on the distance between track segments. One model under consideration is the track maintenance scheduling problem (TMSP) model, which 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 (*30*).

MODEL OPERATION

The model works by executing all three modules for each year in the planning period. Initially the track condition is predicted at the end of the first year and projects are selected and scheduled as described above. Then the process is repeated for the next year with the condition of the track at the end of the first year being used as the new initial condition, i.e. 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, then the condition is projected to the end of the year based on the improved condition. If a track section was a red defect, but it wasn't covered by the budget, then the initial condition is the FRA limit to increase the likelihood it will be maintained the next year. This is repeated until the end of the planning period.

It is anticipated that this model would be run more often than once per planning period. New information about the track will come in as it is inspected and renewal projects are performed, and this may change the predictions for how the track will degrade in the future. Another reason that the model may need to be run multiple times is if planners use it to determine the maintenance budget. The model can provide a view of how much performing the required maintenance will cost and then the budget can be adjusted accordingly.

CASE STUDY

To see how the model performs, a hypothetical case study was performed. The system characteristics are provided in TABLE 1. Characteristics of the track segments are provided in Table 2. It should be noted that since the condition represents the probability of failure, lower condition values represent a better track condition. The model currently uses Weibull values presented by Jeong and Gordon (*10*) with α equal to 3 and β equal to 1,500 million gross tons (MGT) for steel rail fatigue, as these values seemed the most developed, and rail is the most expensive part of the track structure. The values presented by Jeong and Gordon are similar to those presented by Orringer (*6*) and Davis et al (*7*).

TABLE 1: Hypothetical case study system parameters

	Value
Planning period	5 years
Maintenance limit	10%
FRA limit	20%
Maintained condition	5%
Annual budget	$50,000
Fixed maintenance cost	$1,000
Variable maintenance cost	$100 / mile /percentage point
Accident cost	$600,000
Mobilization cost	$100
Mobilization time	2 hours
Train Delay cost	$662 / train-hour (2)
Probability of a derailment given a track failure	0.84% (31)

TABLE 2: Hypothetical case study track segment characteristics

Section	Length (miles)	Annual Traffic Level (MGT)	Existing Condition (%)
1	1	10	38
2	4	10	48
3	2	20	69
4	5	20	72
5	2	20	8
6	3	20	38
7	3	20	35
8	2	20	26
9	1	25	5
10	10	30	31
11	8	30	94
12	6	30	43
13	7	30	50
14	5	30	10
15	2	30	33
16	5	30	20
17	2	40	22
18	8	50	31
19	4	50	17
20	8	50	75

After running the model for the above conditions, it was observed that although the initial track condition was very poor, starting the year with 15 red defects, the model was able to identify those sections and maintain them. A summary of the track conditions over the planning period and the defects at the end of each year is shown in FIGURE 1. It can be observed that the average track condition drastically improved in the first year, and the red defects steadily decreased each year, while the overall track condition on the segment improved. Most of the red defects are the result of deferring maintenance of red defects in previous years until there was available budget for more thorough maintenance.

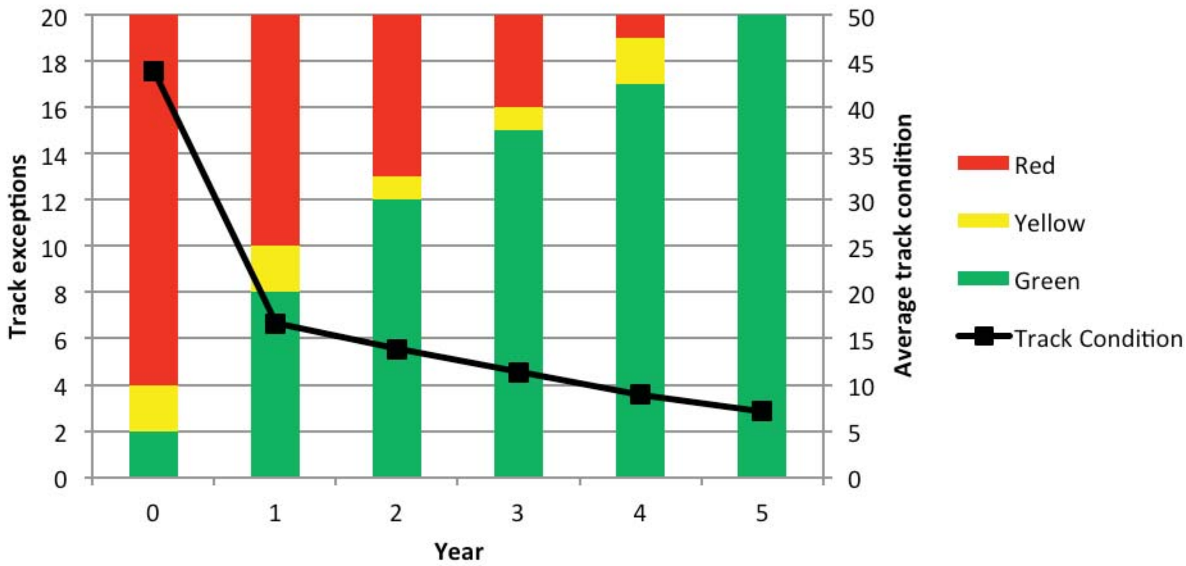

FIGURE 1: Planned Track Condition Improvements

While these results are based on simplified assumptions, it does demonstrate that the model has the ability to reduce the worst case situations in a prioritized manner. By the nature of how the model works, it is always selecting the maintenance projects that result in the best business decisions.

CONCLUSIONS AND FUTURE WORK

The model presented here has the potential to improve track maintenance planning. By considering the entire process in one model, it is possible to improve coordination and prioritization of maintenance activities to make sure that the railroad is keeping the track safe in a way that considers returns.

Some of the 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 continued literature review will take place, efforts will be made to determine which, if any, models are used by North American Class 1 railroads. These models would be validated and aligned with the needs of an operating railroad.

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.

ACKNOWLEDGMENTS

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TABLE OF TABLES AND FIGURES

An Integrated Model for the Evaluation and Planning of Railroad Track Maintenance

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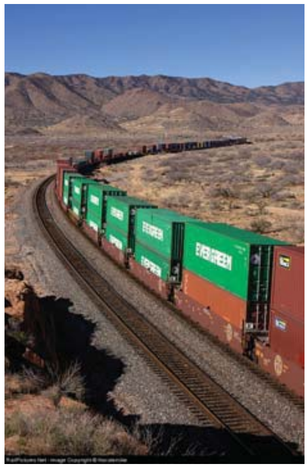
Outline

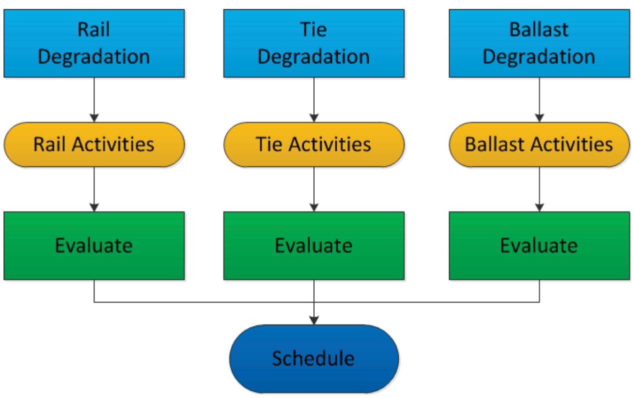
- Introduction
- Model overview
- Module descriptions
- Model operation
- Case study
- Future work



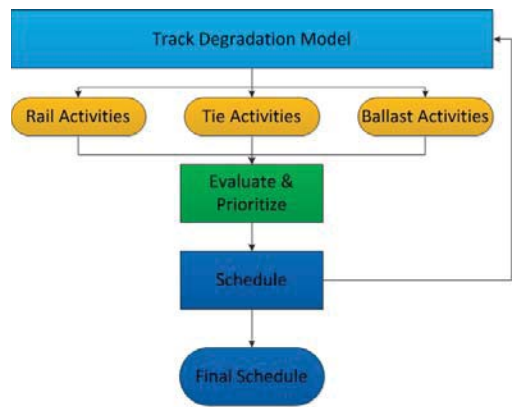
Introduction

- A properly functioning railroad requires all components be maintained in good working order
- Improved planning of maintenance can reduce costs while decreasing the possibility of a service disruption
- There is not currently a comprehensive analytical model for maintenance planning
- An analytical model framework was developed to assist with preventative maintenance planning

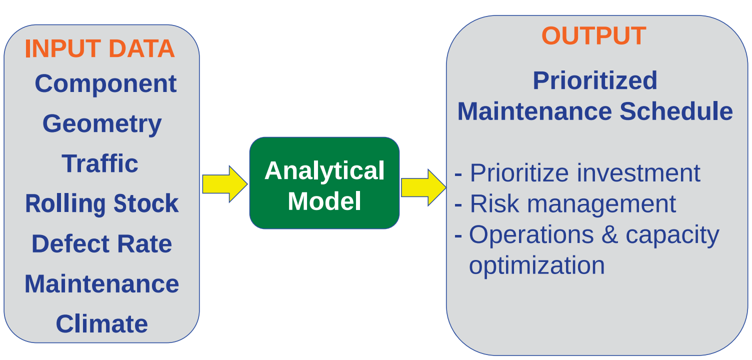
Current practice



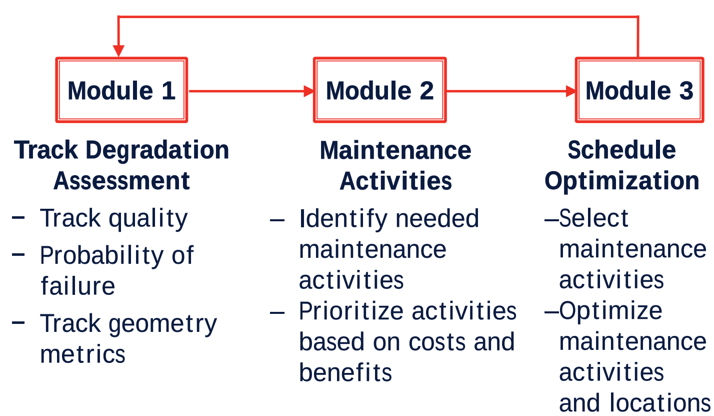
Proposed model routine



Model Concept



Model overview



Degradation models (Module 1)

- Substantial research has gone into railroad track component degradation
- Integrated models are less developed, but more representative of track performance
- Mechanistic and empirical methods are required to represent the variation of the physical breakdown of the track
- The Weibull distribution was selected for development of the model framework

Weibull distribution (Module 1)

- Commonly used for representing time to failure
- Scale factor (β) is based on average life span
- Shape factor (α) determines distribution shape
- Simplicity of form is beneficial for model framework development
- More complete degradation models should be used as they are identified

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

Where:
β = scale factor
α = shape factor
x = time

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Advanced models (Module 1)

- Robust degradation models need to consider a range of factors, such as:
  - Component type
  - Track geometry
  - Traffic levels
  - Climate
- Desired characteristics
  - Mechanistic and empirical basis
  - Consider the existing condition of the track
  - Component interaction
  - Consideration of incremental maintenance
  - Quantitatively indicate component condition

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Activity selection (Module 2)

- The model currently identifies where maintenance needs to be performed, but does not identify specific maintenance activities
- Future research will focus on using case-based reasoning (CBR) for this purpose
  - CBR relies on a case library of historical conditions and solutions
  - The model determines what maintenance activity will be optimal for a defect by comparing it to cases in the library
  - The model becomes more accurate as new projects are completed

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Activity evaluation (Module 2)

- Activity evaluation is based on the benefit/cost (B/C) ratio for each selected maintenance activity
- Gives priority to FRA defects
- Does not consider effects of slow orders

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Activity evaluation – Benefits (Module 2)

- Benefits are measured by the risk reduction from performing maintenance
- Risk = probability x consequence
- Probability of a service disruption
  - Decreases with the application of maintenance
  - Increases with higher traffic levels

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Activity evaluation - Costs (Module 2)

- Direct costs
  - Consist of labor, equipment, travel, etc.
  - Assumed to be proportional to the track condition until further cost data is gathered
- Delay costs
  - Directly related to traffic volume
  - Assume linear delay propagation for all trains affected by a service disruption

Schedule optimization (Module 3)

- Model process
  - Selects maintenance activities considering maintenance and mobilization costs
  - Limited by a budget and time constraints
  - Selects projects with highest B/C first
  - Gives priority to areas where FRA defects are projected to occur
  - Activities are scheduled geographically

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Schedule optimization (Module 3)

- Transportation maintenance scheduling problem model
  - Minimizes transportation costs
  - Considers
    - Maintenance windows
    - Activity sequencing
    - Project clustering

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Model operation

- All three modules will be executed for each year
- The first year uses the given initial conditions
- Each subsequent year, the process is repeated for the next year using the track condition at the end of the previous year
- This is repeated until the end of the planning period

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Case Study

- 20 segments of varying length, traffic, and condition
- 80% were classified as FRA defects
- Where applicable, assumptions were made for broken rail service disruptions:
  - Weibull constants
  - Accident costs
  - Derailment probability

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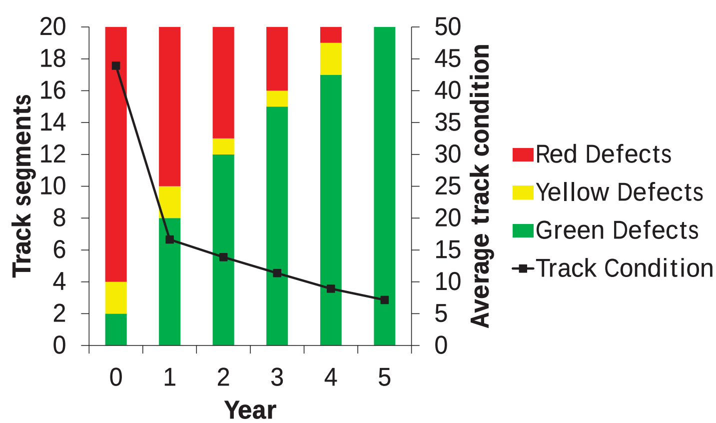
Case study results



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Immediate future work

- Identify or develop degradation models that can be applied to the model
- Risk analysis of track defects
- Improved cost analysis of maintenance activities and service disruptions
- Examine efficiency of maintenance activities in reducing derailment risk

Questions or comments?

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